REAL-TIME ADAPTIVE SYSTEMS FOR BUILDING ENVELOPES

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REAL-TIME ADAPTIVE SYSTEMS FOR BUILDING ENVELOPES

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To the Solar Decathlon Team, 2007.

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It is very rare that you enter into something that you are not too aware off and are supposed to work with people you have never known before, but at the end when you are left with some of the most enriching experiences, personal and professional, along with a bunch of people who will remain very close to you for a long time, you know you have experienced something very special. Solar Decathlon, for me, was one of those experiences.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure 3.13 Aluminum Prototype – Proposed Modifications (Fall, 2007) 38

LIST OF SYMBOLS AND ABBREVIATIONS

PV	Photo-Voltaic
AWPL	Advanced Wood Products Laboratory
CNC	Computer Numerical Control
IMPS	Interactive Music Performance System
NREL	National Renewable Energy Laboratory
ETFE	Ethylene TetraFluoro Ethylene

SUMMARY

The thesis attempts to investigate the issues pertaining to design, fabrication and application of real-time adaptive systems for building envelopes, and to answer questions raised by the idea of motion in architecture. The thesis uses the Solar Decathlon Competition as a platform to base all the research and consequently to verify their applications.

Photo-voltaic (PV) panels and shading devices are two different components of Georgia Institute of Technology's the Solar Decathlon House, located above the roof, that are based on the concept of 'Homeostasis' or self-regulated optimization. For the PV panels, the objective is to optimize energy production, by controlling their movement to track the changing position of Sun, whereas, the objective for the shading devices is to reduce heating or cooling loads by controlling the position of shading devices, thus controlling direct and diffused heat gains through the roof.

To achieve this adaptive feature, it required three layers of operations. First was the design of the mechanics of movement, which tried to achieve the required motion for the PV panels and shading devices by using minimum components and parameters. Second was the design of the individual parts that are consistent with the overall concept of the House. And finally, the third layer is the design of controls that automates the motion of the PV panels and Shading Devices, using a set of sensors that actuate the attached motors. As a final product, there is an attempt to integrate the precision and material efficiency of digital fabrication with the self-regulated optimization of the roof components.

CHAPTER 1

INTRODUCTION

1.1 Adaptation

Adaptation is a characteristic of a system which implies change within the system, as a response to its imposed environment. The development of this change is governed by a set of implicit or explicit objectives for the system.

The concept of Adaptation is central to biology, where it has been defined as a positive feature of an organism that has been favored by natural selection (Sterelny *et al*, 1999).

What needs to be noted is that adaptation, theorized in biology as an evolutionary mechanism, is an extremely long process and may take years before a significant (physical or behavioral) change is observed. But none the less, the concept of adaptation, long-term, short-term or real time has inspired interesting research in fields other than biology.

For instance, Cemgil *et al* have introduced an interactive music performance system (IMPS), which is a computer program that is based on real time adaptation, that "listens" to the actions of a performer and generates responses in real-time. One important goal, for this project, was to design a robust IMPS that performs well for a broad set of performance conditions, e.g. different genres, styles, tempo etc. Authors claim that due to the diversity of the domain, this objective is rather difficult to achieve with rule-based approaches.

In other words, an adaptive system allows for a non-specific solution for a problem case that is diverse and variable.

1.1.1 Real Time Adaptation

When the solutions in the form of changes within the system are observed instantaneously, in response to the varying environmental conditions, the system is said have undergone real time adaptation.

A system can achieve a real time adaptation with or without using a decision making component. A decision making component implies an intelligent feature that is capable of sensing the change of state for an observed variable, is able to process the accumulated input variables and based on a set of defined objectives, is able to initiate a reaction to changing environment. The case of IMPS cited above is an example that uses a decision making tool in the form of a variational extension of the Expectation Maximization algorithm for online parameter estimation. On the other hand, the case of Heliotropism in biological system is an example of a reactionary system that does not include any processing of information.

Heliotropism is the diurnal motion of plant parts (flowers or leaves) in response to the direction of the sun. Heliotropic flowers track the sun's motion across the sky from East to West. During the night, the flowers may assume a random orientation, while at dawn they turn again towards the East where the sun rises. This behavior is exhibited, for example, by the snow buttercup (*Ranunculus adoneus*), an alpine plant. The motion is performed by motor cells in a flexible segment just below the flower, called a pulvinus. The motor cells are specialized in pumping potassium ions into nearby tissues, changing the turgor pressure. The segment flexes because the motor cells at the shadow side elongate due to a *turgor rise*. Heliotropism is a response to blue light. If at night a heliotropic species is covered with a red transparent cover that blocks blue light, the plant does not turn towards the sun next morning. In contrast, if it is covered with a blue transparent cover, the plant does track the sun.

1.1.2 Real Time adaptive system for Building Envelope Design

The United States Department of Energy, Energy Efficiency and Renewable Energy Division defines a building envelope as a "skin" that consists of structural materials and finishes that enclose space, separating inside from outside. This includes walls, windows, doors, roofs, and floor surfaces. It claims that the envelope must balance requirements for ventilation and daylight while providing thermal and moisture protection appropriate to the climatic conditions of the site. Envelope design is a major factor in determining the amount of energy a building will use in its operation. Also, the overall environmental life-cycle impacts and energy costs associated with the production and transportation of different envelope materials vary greatly.

It is suggested that the design team must integrate design of the envelope with other design elements including material selection; day lighting and other passive solar design strategies; heating, ventilating, and air-conditioning (HVAC) and electrical strategies; and project performance goals. One of the most important factors affecting envelope design is climate. Hot/dry, hot/moist, temperate, or cold climates will suggest different design strategies. Specific designs and materials can take advantage of or provide solutions for the given climate.

As is evident, traditionally building envelopes are designed for a specific external environment condition, which is in most cases decided based on the local codes or climate data that has been averaged over several years.

The result is that the building envelope is inherently flawed, as the weather condition is a continuously varying parameter. Moreover, it is either completely isolated from the external environment, and the internal space is then conditioned as per requirement, or building “skin” is provided with temporary “secondary” layers that can be added or removed as desired. The first solution, which relies completely on active strategies, results in a very high energy cost and the latter may achieve the desired balance of space conditioning versus energy cost, but it is a solution that is highly specific and the integration of the layers into the overall building design usually leaves a lot to be desired of.

The thesis, therefore, presents an experimental study into real time adaptive systems as a non-specific solution for diverse environmental conditions that specifically looks at issues pertaining to integration of photovoltaic panels and shading devices for the roof with the building envelope, and the control and automation of their motions. The experimental study was a part of a zero-energy solar house which formed Georgia Institute of Technology’s entry for the Solar Decathlon Competition.

1.2 Solar Decathlon

Solar Decathlon is an international competition, conducted every two years, that invites 20 universities world-wide and challenges them to design, build and operate an 800 sq.ft. Solar-powered house on the National Mall in Washington D.C. The teams are judged for maximizing energy production and optimal energy efficiency, while integrating modern conveniences and engineering systems with architectural design.

The Solar Decathlon 2007 was conducted in October, 2007 and was sponsored by the Office of Energy Efficiency and Renewable Energy at the US Department of Energy, in partnership with its National Renewable Energy Laboratory, the American Institute of Architects, the National Association of Home Builders, BP, the DIY Network and Sprint.

1.2.1 Contests at Solar Decathlon

The teams competing at the Solar Decathlon are judged for the following 10 contests:

1. Architecture (200 pts.)

2. Engineering (150 pts.)
3. Market Viability (150 pts.)
4. Communications (100 pts.)
5. Comfort Zone (100 pts.)
6. Appliances (100 pts.)
7. Hot Water (100 pts.)
8. Lighting (100 pts.)
9. Energy Balance (100 pts.)
10. Getting Around (100 pts.)

The scope of the thesis was limited to address the issues pertaining to the contests of Architecture, Engineering and Comfort Zone. Following are the specifics of these contests (http://solar.gatech.edu):

<u>Architecture:</u>

For a cumulative score of 200 points, the Architecture contest incorporates three facets: Firmness (suitability of skin, materials), Commodity (facility of program integrated with function), and Delight (comprehensive impression of originality). The collaboration of the former factors will be judged by a jury of professional architects to conclude which team has designed an innovative and attractive green house design.

<u>Engineering:</u>

Two juries, Energy Analysis and Engineering Design/Implementation, are used to decipher the technological advancements to the Solar Decathlon house. For the Energy Analysis Contest, students are required to fabricate a model predicting the annual energy performance of the respective house design. They will be observing how this model improved the form and technology utilized in the Decathlon house. In the

Engineering Design/Implementation Contest, the teams are assessed on the building envelope, indoor environmental control, mechanical, electrical, and plumbing systems.

Comfort Zone:

There is a delicate balance in which our indoor environments comfortably operate. Teams must effectively design their house to consistently achieve the predetermined target temperature and humidity. The tight temperature range of 72°F/22.2°C - 76°F/24.4°C) and relative humidity of (40% - 55%) are defined as the optimal comfort zones. The competition is judged by a panel of experts in building heating, cooling, and ventilation.

1.2.2 Need for Real Time Adaptive Systems

The two systems that were tested for real time adaptations were the operability of photovoltaic panels to achieve optimum angle and the operability of the roof-integrated shading devices.

1.2.2.1 Operability of Photovoltaic Panels:

According to the National Renewable Energy Laboratory (NREL), a national laboratory set up for renewable energy and energy efficiency research and development, if the panels are mounted on a tracking device that follows the sun, it allows them to capture most of the sunlight over the course of the day. Sun tracking devices, in fact, can help increase the power generation by 30% or more (http://en.wikipedia.org/wiki/Photovoltaic_array). Moreover, it allows the panels to adjust to the varying angle requirements in accordance to their location and changing climate conditions over the entire year. This feature would provide the Solar Decathlon house with the capability to be relocated without a substantial modification to the set up of the PV array.

1.2.2.2 Operability of Roof-integrated Shading Devices:

One aspect that has been consistent with passive solar strategies is the use of thermal mass, which usually results in a very opaque envelope with small openings. It was felt by the design team that there is a case for challenging this typology, and hence allowing for the maximum possible propagation of sunlight (direct or diffused) inside the house.

The above design objective dictated the selection of most of the material for the Solar Decathlon house, including the roof. One roof panel comprised of three layers of a translucent plastic material called ETFE, the top two layers effectively formed an "air pillow" and acted as rain screen, while the bottom two layers was filled with an insulation material called "aerogel".

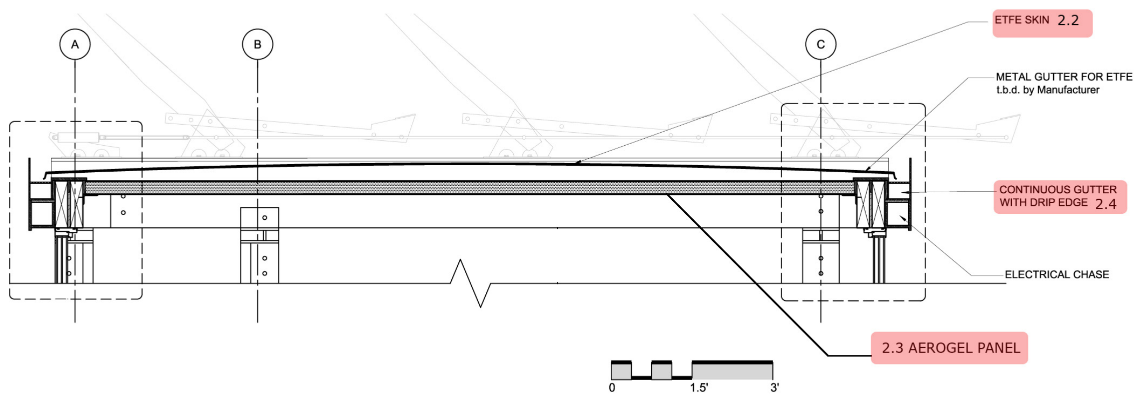

Figure 1.1: Transverse Section through the ETFE roof.

The translucent roof, although allows a good quantity of light through, but depending on the location of the house, it may cause to increase the cooling load. This was confirmed by simulating the three different options (1-No Shading, 2-Fixed Shading and 3-Controlled Shading) for the roof integrated shades. The results were as follows:

Table 1.1: Yearly Heating and Cooling Loads for Option 1

month	cooling(kWh)	heating(kWh)
1	534.171	1392.217
2	776.054	1042.467
3	1329.775	657.932

Table 1.1: Continued

month	cooling(kWh)	heating(kWh)
4	1975.288	382.008
5	2363.938	95.042
6	2528.433	10.567
7	2752.458	6.682
8	2666.287	7.276
9	2121.278	29.041
10	1673.820	358.899
11	926.845	802.277
12	535.340	1224.300
Yearly	20183.687	6008.708

Table 1.2: Peak loads for Option 1

	Peak load (ton)	Time
Cooling	3.7	Jul 2, 2pm
Heating	2.67	Feb 10, 7am

Table 1.3: Yearly Heating and Cooling Loads for Option 2

month	cooling(kWh)	heating(kWh)
1	112.505	1608.919
2	171.589	1214.863
3	314.983	782.023
4	534.529	432.364
5	792.734	109.870
6	1021.900	11.870
7	1178.513	7.224
8	1112.854	8.064
9	872.803	32.051
10	615.566	392.427
11	273.627	887.294
12	122.337	1397.992
Yearly	7123.94	6884.961

Table 1.4: Peak Loads for Option 2

	Peak load (ton)	Time
Cooling	1.465	Jul 3, 4pm
Heating	1.657	Feb 10, 7am

Table 1.5: Yearly Heating and Cooling Loads for Option 3

month	cooling(kWh)	heating(kWh)
1	151.242	1422.719
2	214.647	1075.548
3	371.922	693.105
4	595.713	403.687
5	828.973	102.635
6	1040.170	11.919
7	1191.999	7.279
8	1128.566	7.958
9	903.980	31.439
10	675.424	373.783
11	329.564	829.614
12	162.291	1254.607
Yearly	7594.491	6214.293

Table 1.6: Peak Loads for Option 3

	Peak load (ton)	Time
Cooling	1.465	Jul 3, 4pm
Heating	1.656	Feb 10, 7am

The results for option 1 with extremely high cooling loads validate the use of shading devices for the translucent roof. Option 2, which is equivalent to having an opaque roof shows an increase for the heating loads as it does not capitalize on the passive gains possible through the roof. Option 3 with controlled shading (in low resolution) implying an open condition when passive heat gains are desirable and a closed position when cooling is needed shows a fairly balanced results for both heating and cooling loads. The results from Option 3 can be further improved to reflect the lowest possible loads, if the shades are controlled in real-time based on the sensor readings from inside the house.

1.2.3 Objectives for Solar Decathlon

<u>Photovoltaic Panels:</u>

To optimize energy production, by controlling their movement -

1. To track the changing position of Sun during the course of a day.

2. To adapt to a different location

Shading Devices:

To reduce heating or cooling loads by controlling the position of shading devices, thus controlling direct and diffused heat gains through the roof.

1.2.4 Methodology

Before the issues of controlling the motion could be addressed it was required to develop the operability and fabrication logic for both Photovoltaic panel system and the Shading Device system. Identification of all the parts involved and their sources, whether in-house or off-the-shelf, needed to be decided. It was also assumed that if the PV panels and shades could be operated manually to achieve the desired results for operability, the issue of automation and hence controls would become a secondary layer of system development.

The next chapter provides a detailed catalog of the design development and the matrix of decision making under which the two systems have been developed.

CHAPTER 2

DEVELOPING THE ARCHITECTURE OF MOTION

2.1 Summer 2006 – Concept Design

2.1.1 Operable Photovoltaic Panels

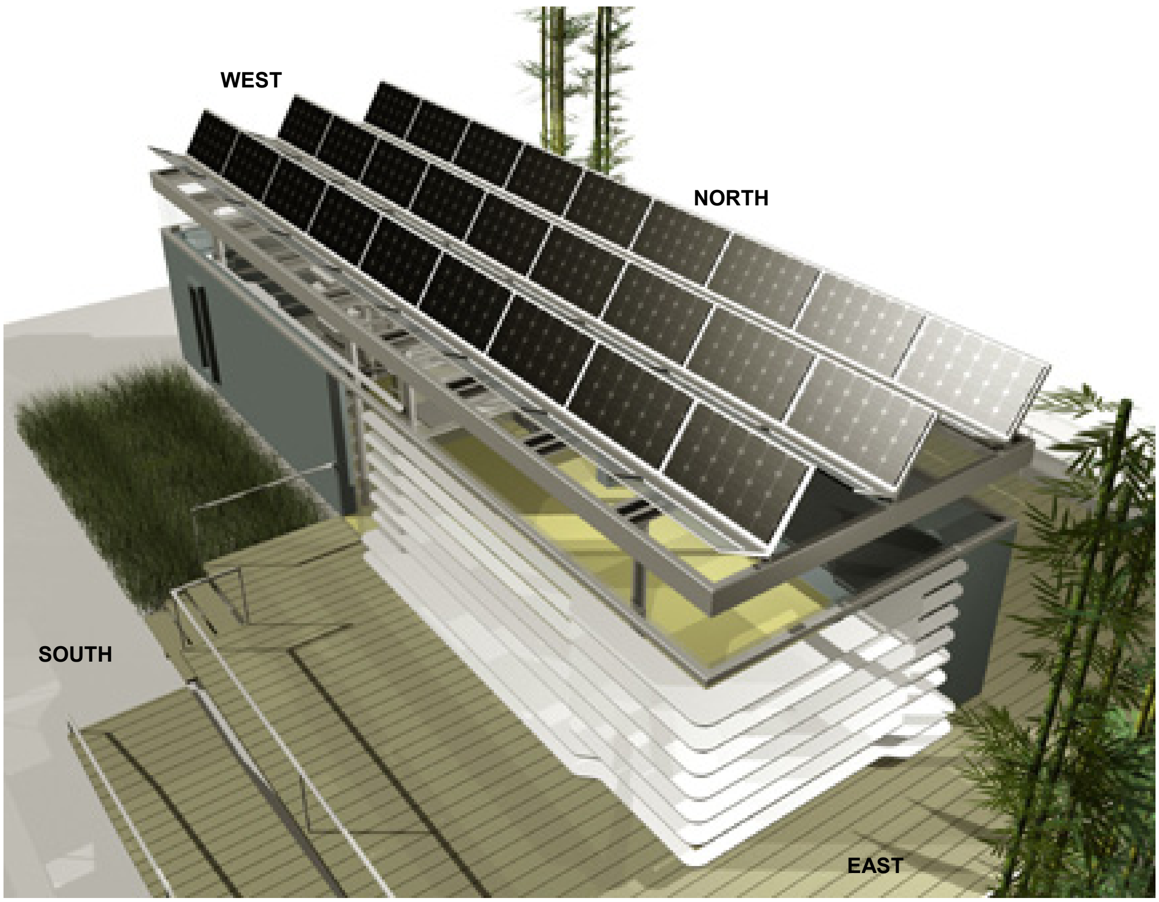

Figure 2.1 Final Conceptual Design after Summer, 2006.

After the Summer charette of 2006, the final conceptual model that was arrived at had 27 roof-mounted photovoltaic panels arranged in 3 rows of 9 panels each. The design had one integrated unit with unified mechanism for the PV panels and the shading devices; this meant that the PV panels and shading devices were constraint to move together.

The PV panels were mounted onto an Aluminum frame, which was fixed to a rotating shaft that connected all the 9 panels in one row. The shaft acted as an axis for the rotational motion that was limited to North-South directions.

To effectively track the motion of the sun, the PV panel support mechanism should have two axis of rotation, one along the east-west and the other along the north-south (http://www.solarray.com/Images/PDFs/SitingActive.pdf). The reason to opt for an east-west axis of rotation was more conceptual than practical, which addressed the issue of maintaining a uniform iconography that of a pair of “wings” that embrace the sun, irrespective of the position of the panels.

Even though the decision to adopt1-axis, North-South tracking was conceptual, it definitely had positive practical implications for the design team. It meant not only a simpler tracking system, the mechanics of which could be designed and manufactured using the available in-house facilities, but also the cost and time involved would also be lower. Also, some studies have found the North-South tracking for maximum irradiance to be more efficient than East-West tracking (Appelbaum *et al*, 1994).

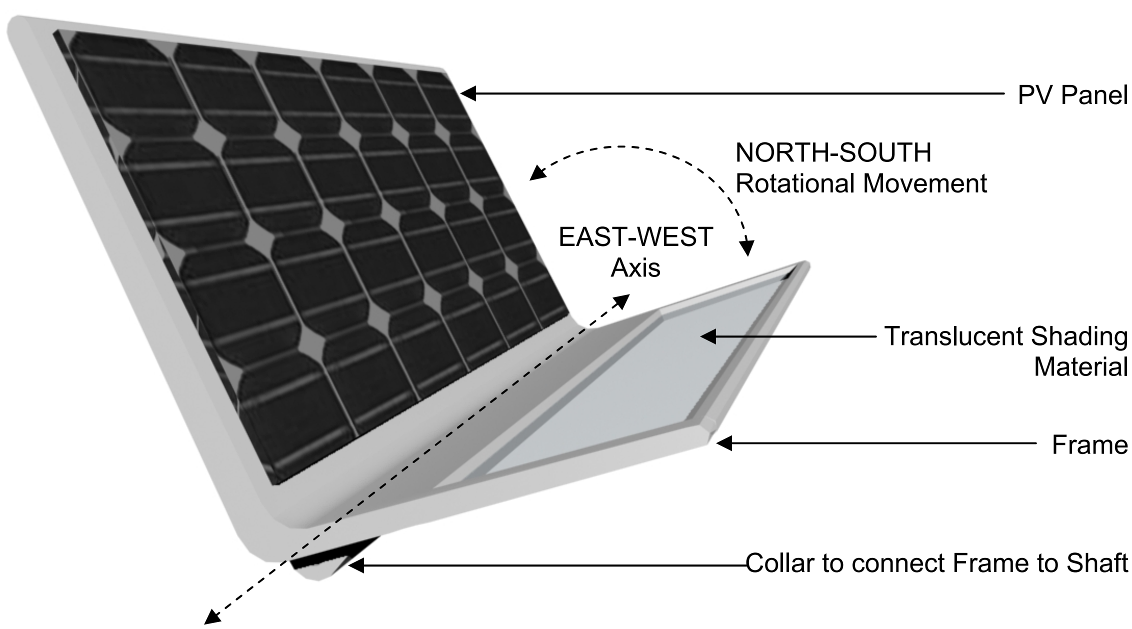

Figure 2.2 Single unit (Summer, 2006).

2.1.2 Operable Roof-integrated Shading Devices

The conceptual design of summer 2006 had the shading devices and PV panels as one integrated system, as shown in Figure 2.2. This considerably limited the functionality of the shades, as it led to less shading during summer when the inclination angle of the sun is high and more shading during winter when the angle is low, thus allowing more gains in summer and fewer gains in winter.

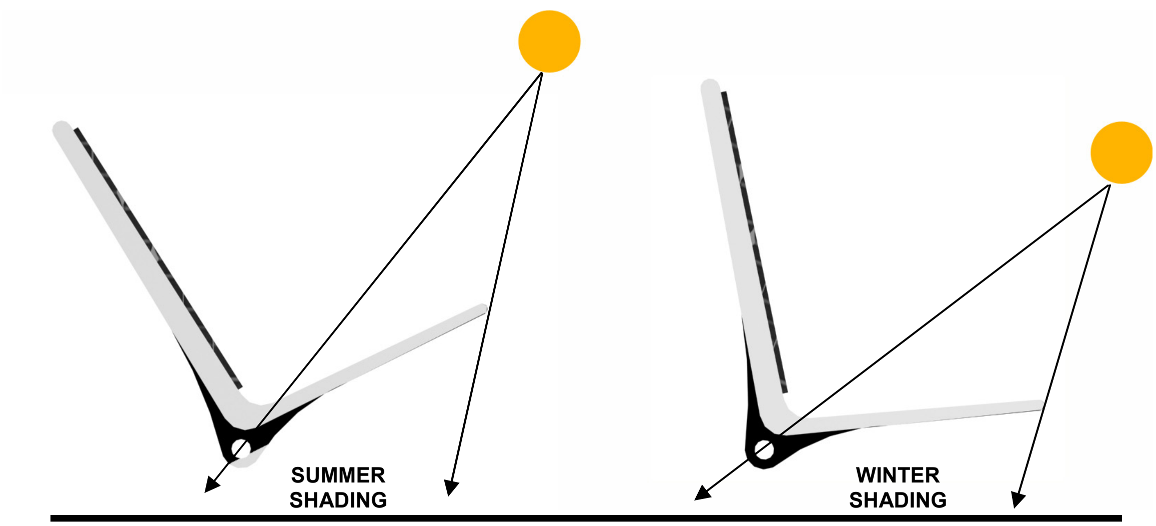

Figure 2.3 Summer and Winter Shading (Summer, 2006).

2.2 Fall 2006 – Modification I

2.2.1 Operable Photovoltaic Panels

Based on the observations and analysis of the previous design, it was decided to separate the two systems completely. The operable photovoltaic panels were now modified to move independently from the shading devices. Even though the two systems were separated, they needed to achieve the same visual symbolism ("wings") attempted by the previous design. This architectural intent defined the scope and provided the constraints under which the two systems were required to be developed.

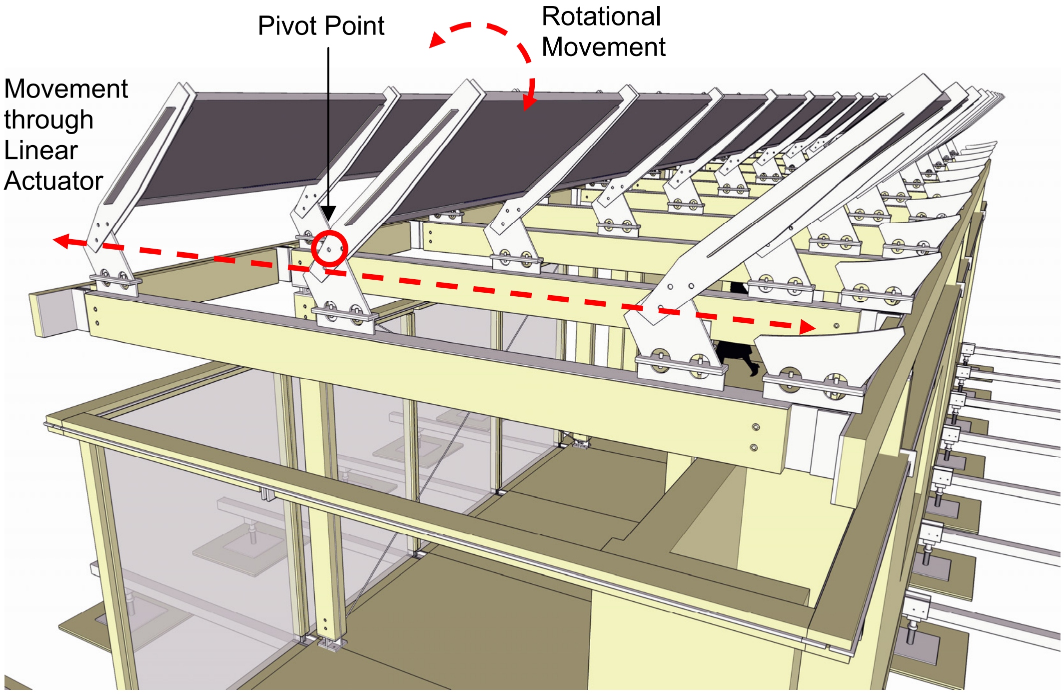

Figure 2.4 Operable Photovoltaic Panels (Fall, 2006).

Modification I involved replacing the rotating shaft that provided the rotational movement to the panels with rods that operate linearly using linear actuators in the north-south direction, while at the same time rotating the panels along the east-west axis through a pivot point. This implied a total of 9 linear actuators for 9 bays of the PV panels. This change solved three issues; one was the elimination of the significantly high rotational torque that was required to rotate a single shaft connected to 9 PV panels, second was the requirement of a stable support structure for dynamic structural loads (generated by PV panels) and third was the fact that it visually aligned the structure for the PV array with the structure of the house, thus achieving an ideally clean solution.

On the other hand, 9 actuators, each with their support individual support mechanisms, made the design very unrealistic in terms of cost and number of parts. Also due to eccentric loading of the pivot point, it made the conversion of linear to rotational motion fairly inefficient, thus increasing the load on the actuators.

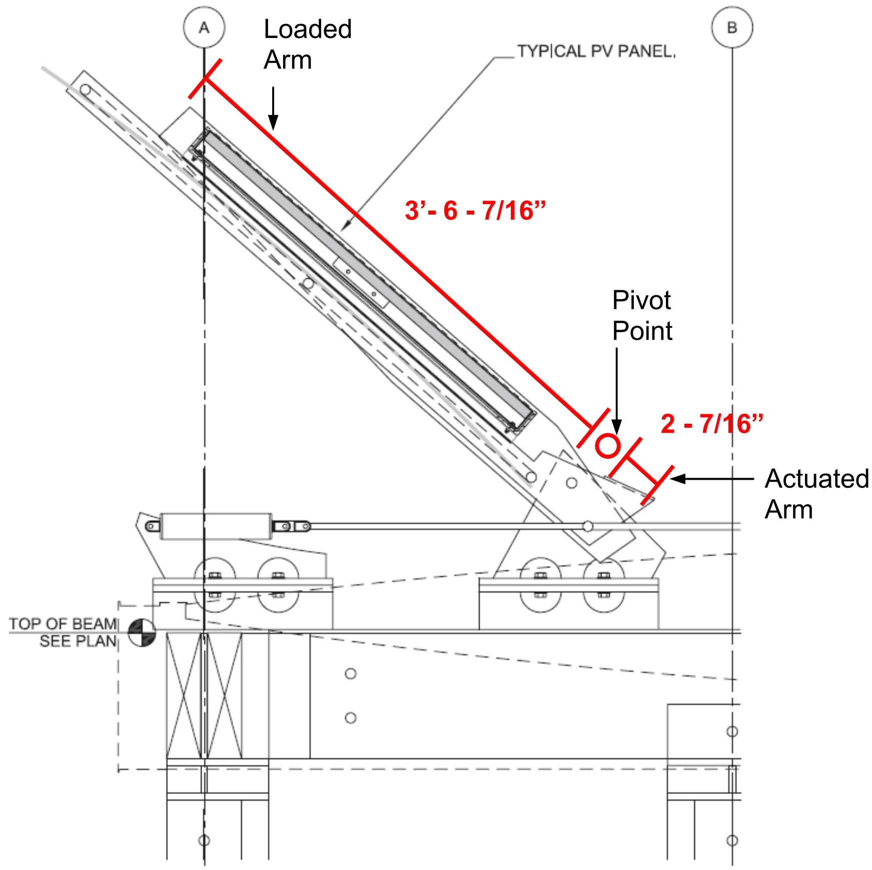

Figure 2.5: Typical PV Panel – eccentric loading of Pivot Point (Fall, 2006).

2.2.2 Operable Roof-integrated Shading Devices

The design for the shading system was developed along the same lines as the PV panels, with 9 actuators controlling the motion of the shades. Each actuator had 3 shades attached to it, and mechanical parts for the actuators and structural supports were again aligned to the existing roof structure.

One corner of the shades was attached to the rod, connected to the actuator, while the sides of the shades had the provision to slide along the pivot point. This allowed the shades to slide linearly as the linear actuator starts to retract (Figure 2.6) and as the shade-rod connection point reaches the pivot point the shades rotate until they are parallel to the PV panels (Figure 2.7).

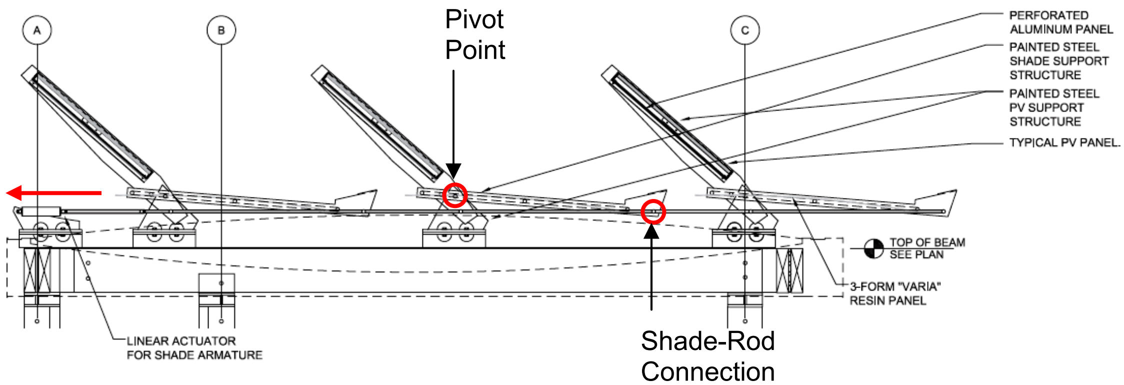

Figure 2.6 Typical section – shades in full extension (Fall, 2006).

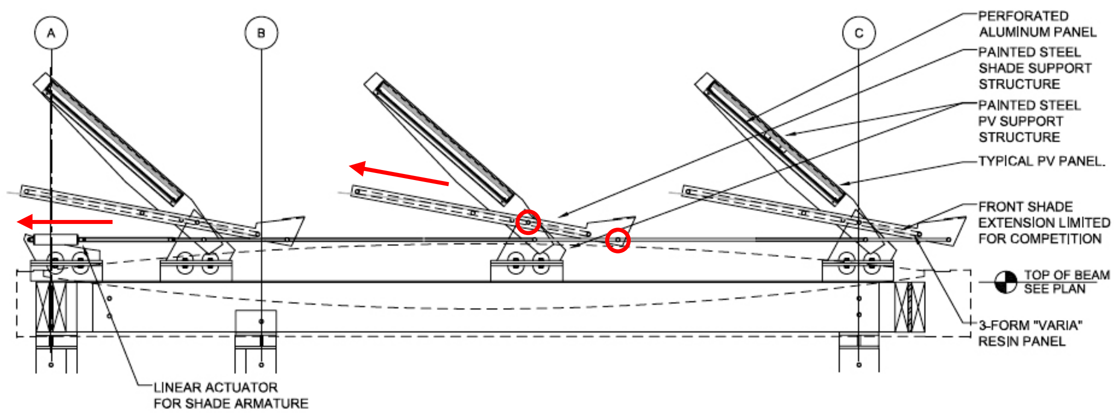

Figure 2.7: Typical section – shades in half extension (Fall, 2006).

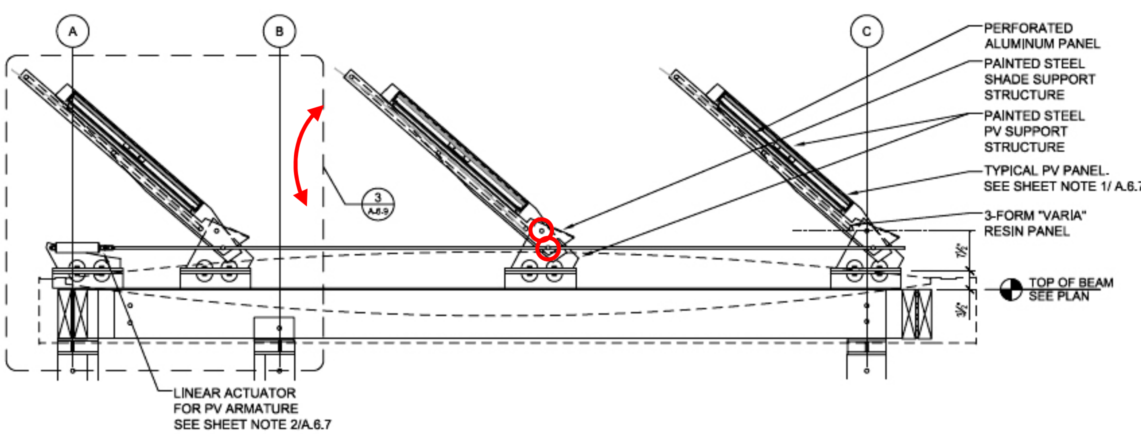

Figure 2.8 Typical section – shades in full retraction (Fall, 2006).

Although the roof-integrated operable shades were successfully combined with the operable PV panel system, but the use of 9 linear actuators, one for each bay making it 18 in total, added to the high equipment cost. Also the shades move about 3'-4" linearly in the north-south direction, but there seems to be no provision for the linear actuator to accommodate such a significant length. Moreover, as the shades slid on the pivot point, there is an inherent friction in the system, which would add to the load of the actuators.

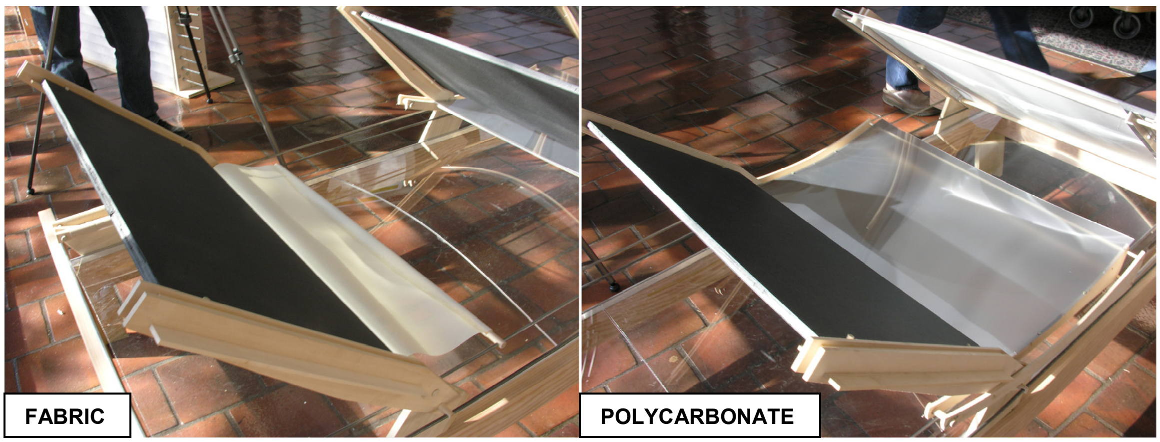

Figure 2.9 Prototyping material study – Operable Shades (Fall, 2006).

There was also an attempt to understand and explore different material options that could be accommodated using the same mechanism. Options that were looked into were transparent polycarbonate and fabric. Option with fabric was taken out of contention as it required an additional spring loaded mechanism that would roll the fabric in the retracted position, but more importantly it failed to achieve the formal requirements set at the onset of the design process.

2.3 Spring 2007 – Modification II

2.3.1 Operable Photovoltaic Panels

2.3.1.1 Iteration A

To eliminate the use of 9 actuators to operate the PV panels, the design team went back to the concept used for the initial design, which was connecting the PV panels longitudinally in the east-west direction. The difference was the use of only one rotating shaft instead of three, therefore replacing 9 linear actuators with 1 rotational actuator / a motor.

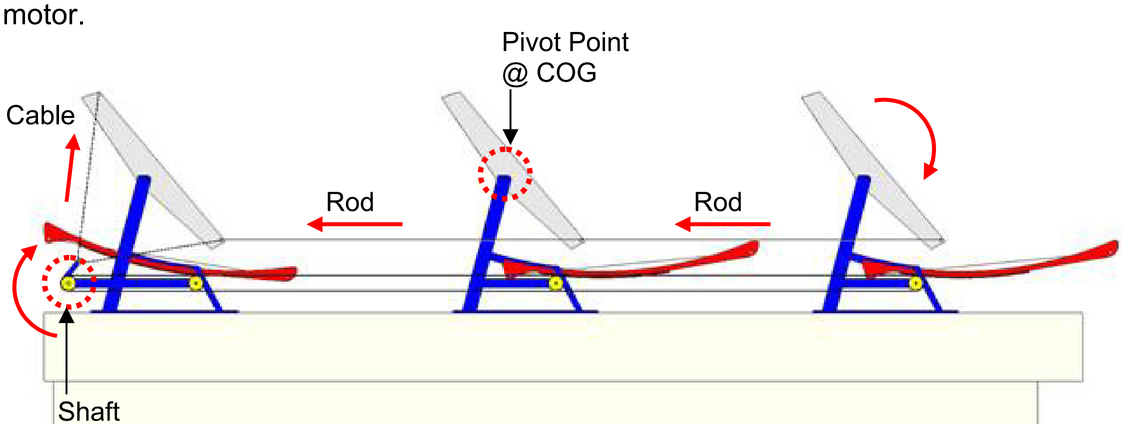

Figure 2.10 Typical Section – Operable PV Panels (Spring, 2007).

The design made use of rods to connect the PV panels in a bay, which was tied, using steel cable, down to a shaft located on the north edge of the roof. The shaft was then provided the rotational torque using a rotational actuator. As there was only one shaft to rotate 27 PV panels, it was important to reduce the load on the actuator. Therefore, to avoid the eccentric loading of the previous design, the pivot point was relocated to the center of gravity of the PV panels, which in this case was effectively the center of the frame supporting the panels.

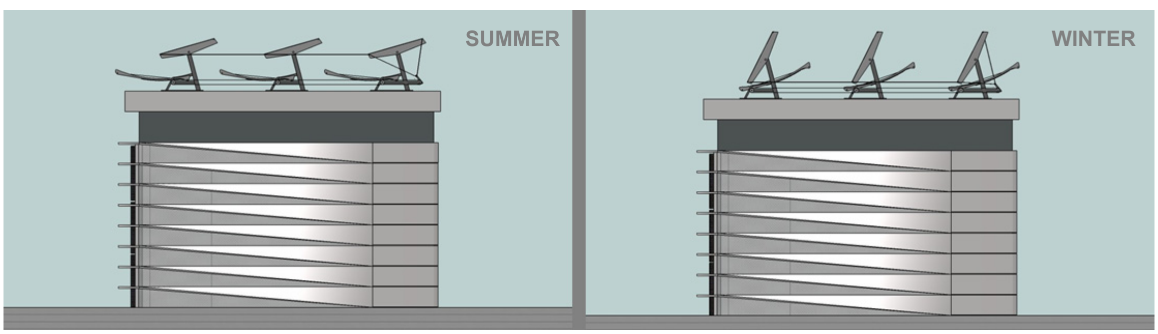

Figure 2.11 PV Panel and Shades – summer & winter positions (Spring, 2007).

Even though it was an effective transfer of motion and had a clear structural logic, it was built up of a number of parts whose visual organization was unclear and contributed little to highlight the desired formal geometry for the panels and shades.

2.3.1.2 Iteration B

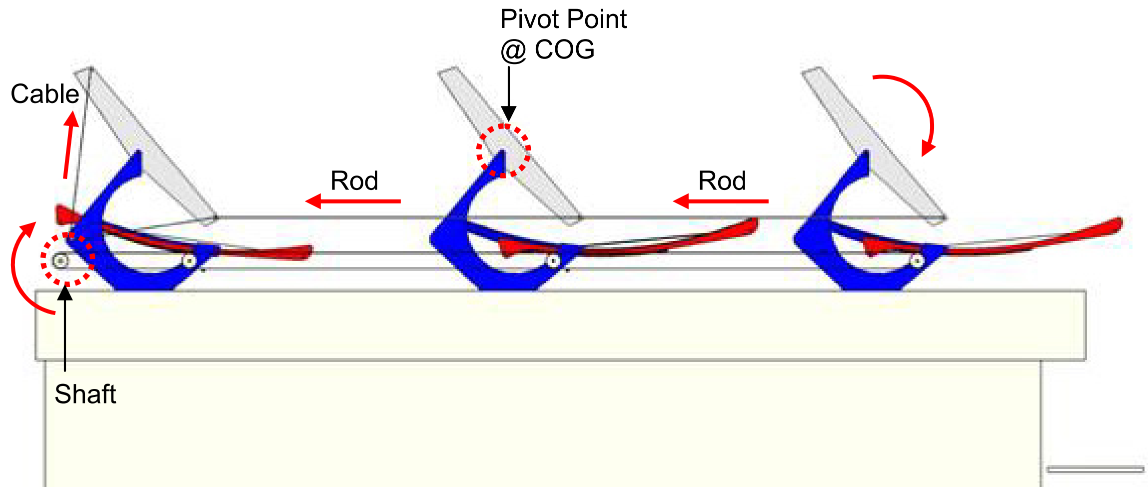

Figure 2.12 Typical Section – Operable PV Panels (Spring, 2007).

The design underwent a second iteration, where the modifications were made only to the profile of the PV support and rest of the design aspects, like the mechanical logic remained the same. The number of parts was reduced and an attempt was made to incorporate different components into a single profile, thus making the organization much clearer and apparent.

One drawback to the introduction of this new geometry was that it made the profile more prominent than that of the PV panels and shades, which was one of the main intentions of the design team. It also made the gesture to the “wings” it little more unclear and less evident.

2.3.2 Operable Roof-integrated Shading Devices

The design of the shades remained the same in both of the above iterations. The motion of shades was based on the same principles as that of the panels, except for the fact that it used 1 rotating shaft per 9 shades in one row, and each of the shafts were then connected to a header shaft that was attached to one rotational actuator.

The design made use of rack and pinion detail to move the shades. The rack was incorporated along the two side frames of the shades, while the rack was mounted onto a shaft that was rotated using a drive sprocket attached to the rotational actuator. The motion was transferred from the actuator to the shafts using chains.

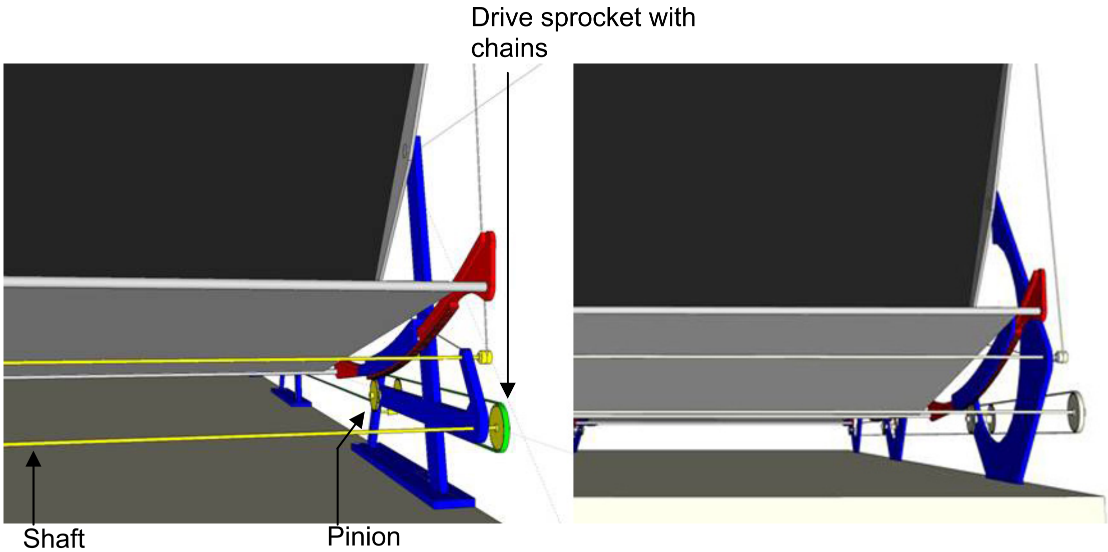

Figure 2.13 Detail of Operable Shades (Spring, 2007).

One of the observations regarding the design was again the large number of parts that were required and their respective organization which could be improved. The motion of shades was not smooth and needed some refinement. Also exposing the drive mechanism was something that the design team believed could be avoided. But apart from these, Modification II proved to be a functional solution and a working prototype was used as the necessary proof of concept.

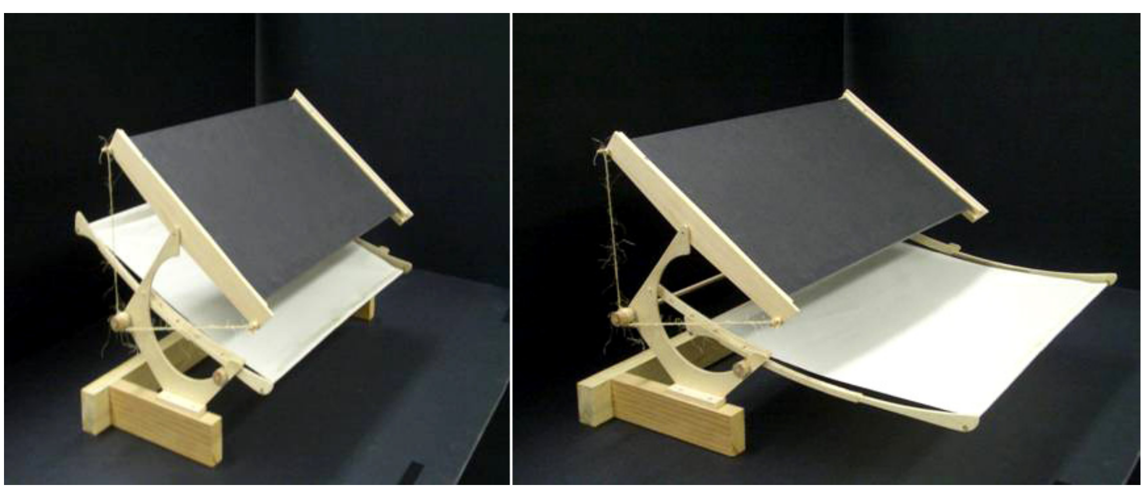

Figure 2.14 Prototype of Operable PV & Shades (Spring, 2007).

2.4 Spring 2007 – Modification III

2.4.1 Operable Photovoltaic Panels

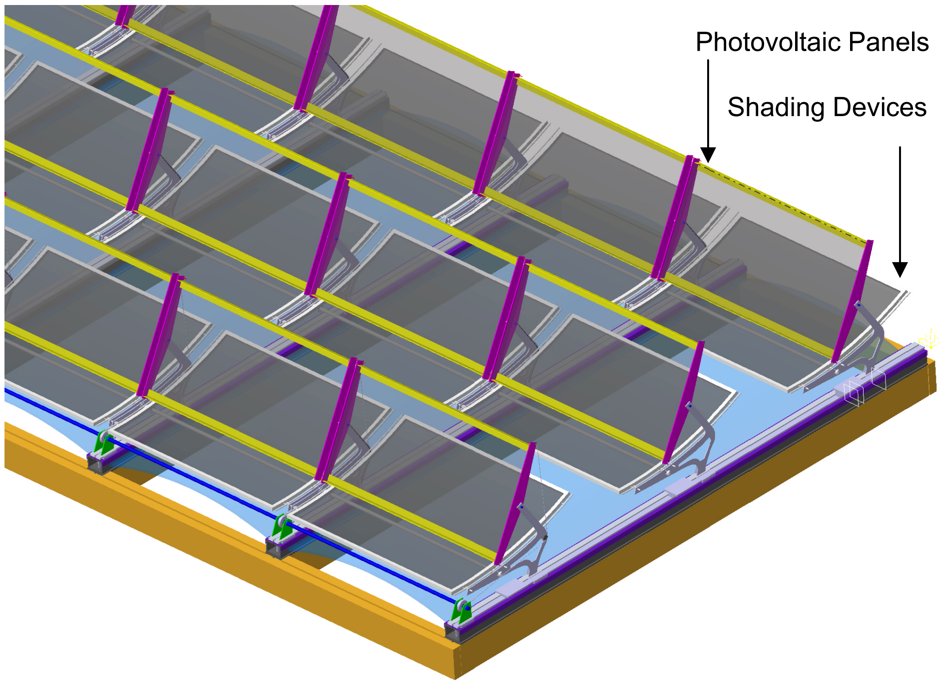

Figure 2.15 Digital Prototype of Operable PV & Shades (Spring, 2007).

Based on the observations from Modification II, the design for the operable photovoltaic was further refined. There were features that continued from Modification II, while others were replaced.

Design features that continued from Modification II:

1. All the 27 PV panels were moved from a single shaft, attached to the first panels through steel cable.
2. The center of rotation was still the center of gravity of the PV panels.
3. The rotating shaft was attached to a rotational actuator / motor to drive the PV panels.

Design features that were modified to incorporate the observations from Modification II:

1. It was decided to use only cables to connect the PV panels so that the dead load could be reduced.
2. The above feature necessitated the relocation of the rotating shaft from northern edge of the house to the southern edge, as the cables functioned only in tension.
3. Also there was a need to make the PV panels spring loaded as the cables were unidirectional.
4. The shape of the PV panel support was altered to align it to the profile of the PV panel and the shades.

The design team felt that it would be beneficial to generate a fully parametric model of the PV panels and shades to achieve a very detailed and realistic representation of the operable systems. Also the ability to change the parameters would allow verifying the possibility of motion and indicating any collisions that could be present. This proved to very crucial decision as it required incorporating all the parts in the correct size to make the model work, which helped in generating a parts list that could be checked for availability in the market. Also parametric modeling allowed a part to be changed according to availability without reworking the entire model. “Digital Project” was chosen as the 3D parametric modeling platform. Below are the results of the “simulation”:

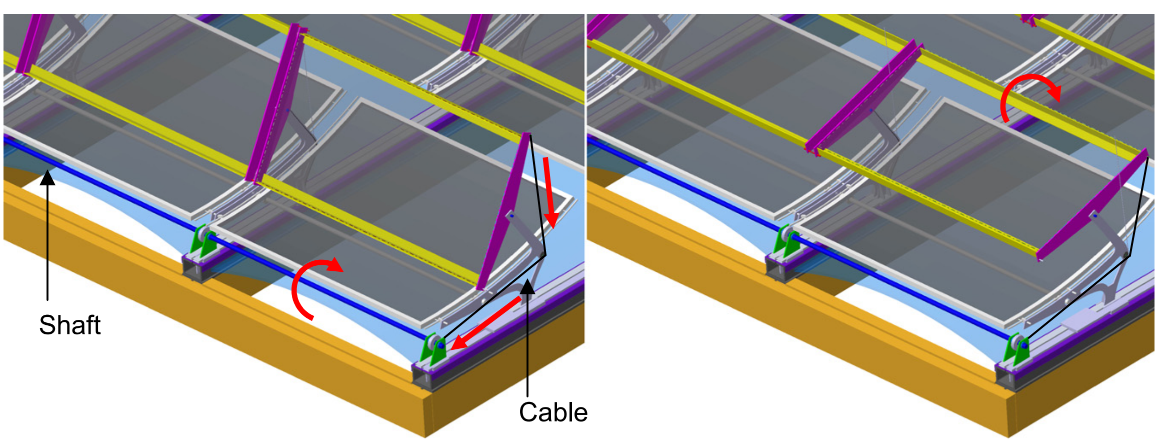

Figure 2.16 Verifying motion of PV panels (Spring, 2007).

After further modifications to the PV support profiles and establishing all the required dimensions, a half-scale prototype was made using the available CNC facility at the Advanced Wood Products Laboratory. The dimensional information was extracted directly from the parametric model and programmed using Computer Aided Machining software (AlphaCAM), which was then used to cut the material on the CNC machine. This ensured that the dimensional accuracy of the digital model was transferred directly to the physical prototype.

The following video shows the prototype with the photovoltaic panels in action:

Figure 2.17 Prototyping motion of PV panels-Spring, 2007.
(deo_vishwadeep_200712_mast_pv-motion.mpg, 2.92 mb)

2.4.2 Operable Roof-integrated Shading Devices

Changes made to the shading devices in Modification III were more drastic as compared to those made to the PV panel supports, but there were few features that remained from Modification II. These were:

1. One rotating shaft was used to move nine shades in a row, which implies there was still a total of three shafts that were used.

2. Rack and pinion detail was used to move the shades, with the rack attached to the side-frames of the shades, while the pinion attached to the shaft.

The changes from the previous version were:

1. Use of cables was completely eliminated.
2. Instead of using a fourth shaft that was attached to the actuator, Modification III made use of a split system in which each of the rows had its own actuator, thus avoiding unnecessary connecting chains and drives.
3. All the hardware to move the shades were relocated to be within the PV supports and under the shades themselves, thus providing a visually clean solution.

Images below show the digital prototyping and verification from Digital Project for the shade motion:

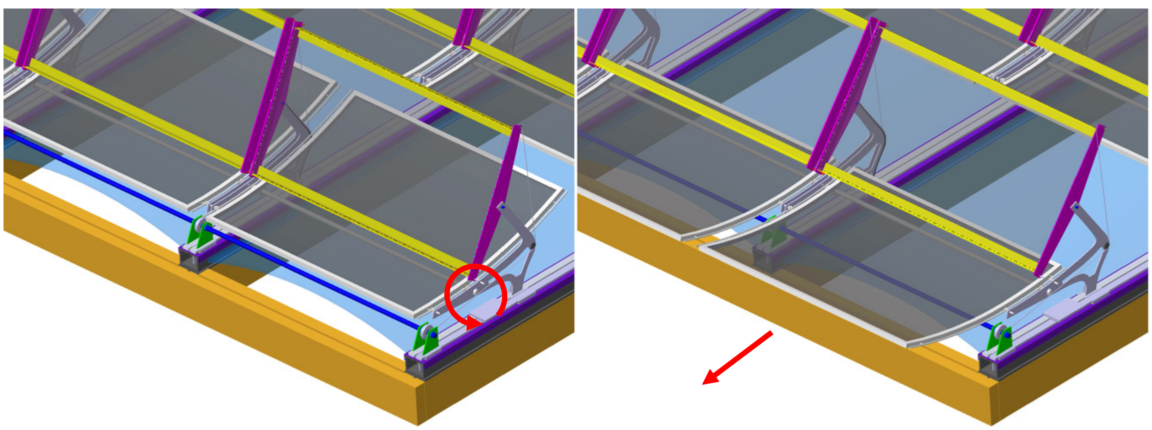

Figure 2.18 Verifying motion of Shading Devices (Spring, 2007).

Again an attempt was made to digitally fabricate all the components using the in-house facilities at the AWPL, including the rack and pinion. This was decided based on the fact that curved side-frames for the shades would be out of metal and the chances of availability of a curved metal rack that matched the desired were extremely low. It was then decided to go ahead and test the geometry using plywood at half scale. It was found that the fabrication of the rack and pinion would prove to very difficult and timeconsuming, as the attempts made for the half-scale prototype failed to provide any satisfactory results. (Figure 2.18)

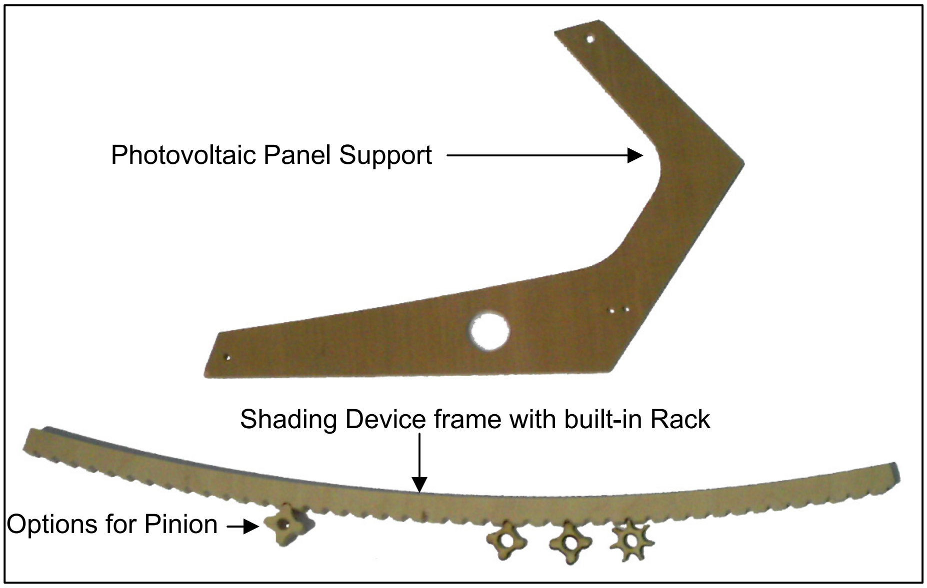

Figure 2.19 Digital Fabrication of components (Spring, 2007).

For the half-scale prototype, an off-the-shelf nylon rack was chosen as it can be made to perform in a curved profile. The following video shows the functioning of the shades with an actuator:

Figure 2.20 Prototyping motion of Shades-Spring, 2007.
(deo_vishwadeep_200712_mast_shades-motion.mpg, 1.95 mb)

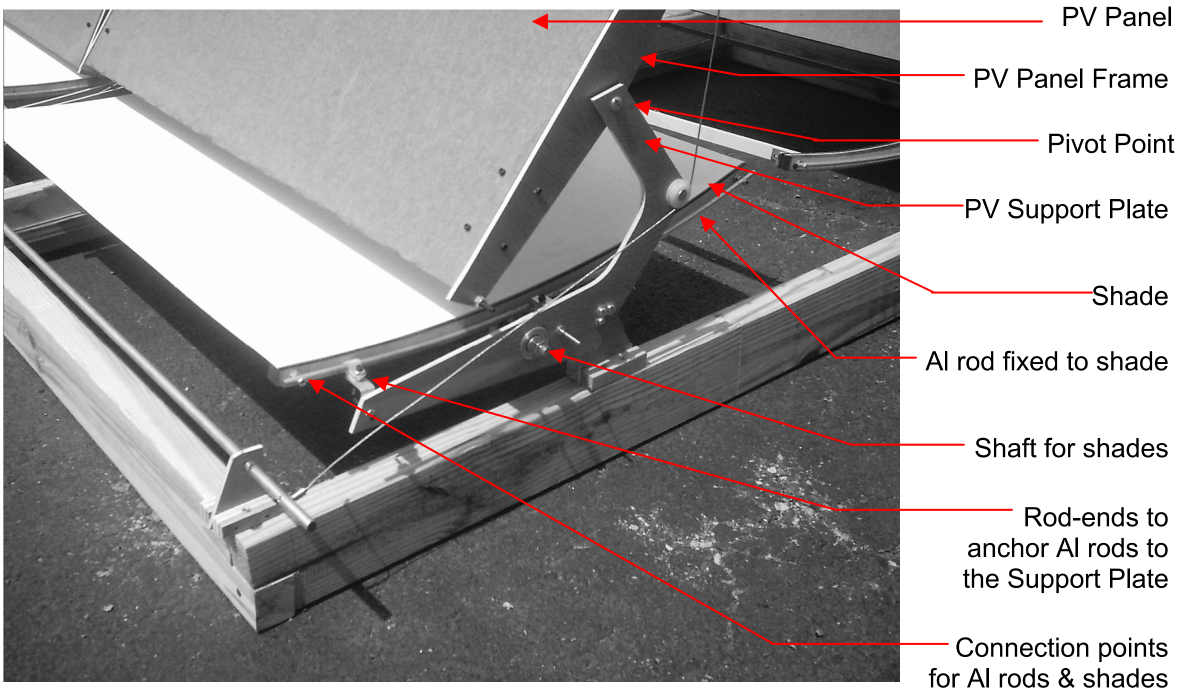

Figure 2.21: Half-scale Prototype (Spring, 2007).

Even though the prototype was a sufficient proof of concept to advance to full-scale mock-ups and actual fabrication, there were two main aspects that still needed to be addressed; one was regarding the profile of the photovoltaic supports, while the other area of concern was the actual time-line for the project.

In regards to the first issue it was felt that even though there had been an attempt to adapt the profile of PV support so that the panels and shades are prominently highlighted, there still exists a significant visual incoherence. Moreover, the fact that the pivot point came up to the center of gravity of the panel frame, made the supports a very visible part of the arrangement.

A decision was taken, by the architectural design team, to move the pivot point back to a lower level. This design decision proved to be a retrograde one, as it implied that the design of the mechanics for the operation of the photovoltaic panels went back to the stage of Modification I, and also because the work that had been done till now could not be adapted to the new changes.

This implied that considering the time-line for the project, the team was required to convene on a decision regarding the operations of the photovoltaic panels, as it practically required completely reworking the strategy for the PV array. The decision that was taken was to limit the adaptability of the photovoltaic panels to a set of angles, with each of the panel being manually adjusted to the desired angle.

The following chapter describes the sequence of steps that were undertaken to refine and fabricate the final photovoltaic and shading device assembly, and its subsequent installation on to the roof of the Solar Decathlon House.

CHAPTER 3

FABRICATING MOTION

3.1 Summer and Fall 2007 – Final Design and Fabrication

3.1.1 Phase I – Profiling the photovoltaic support

The first phase of final design development involved arriving at a profile for the Photovoltaic panel support, which could integrate the formal requirements set down at the beginning of design process with the relocation of the pivot point, as set forth in the observations of the previous design. The objectives, to reiterate, were:

- To ensure that the supports make a minimal formal gesture that compliments PV panels and the shading devices, in achieving the iconography of “wings”.
- To incorporate, within the supports, the shaft for the shading devices, pivot point for the photovoltaic panels and a support mechanism for the shades.
- To arrive at a detail that allows the supports to be anchored back to the structure of the house.

During the investigation to arrive at a profile, an interesting fact emerged that offered different methodologies to seek the optimum profile. As the dimensions of the PV panels and form and size of the shading devices were fixed, and regulations for the competition prohibited any projections outside the footprint of the building envelope as it affected the total covered area, the PV panels and shading devices had to be placed at different intervals.

Under the above circumstances, the different methodologies that could be adopted were:

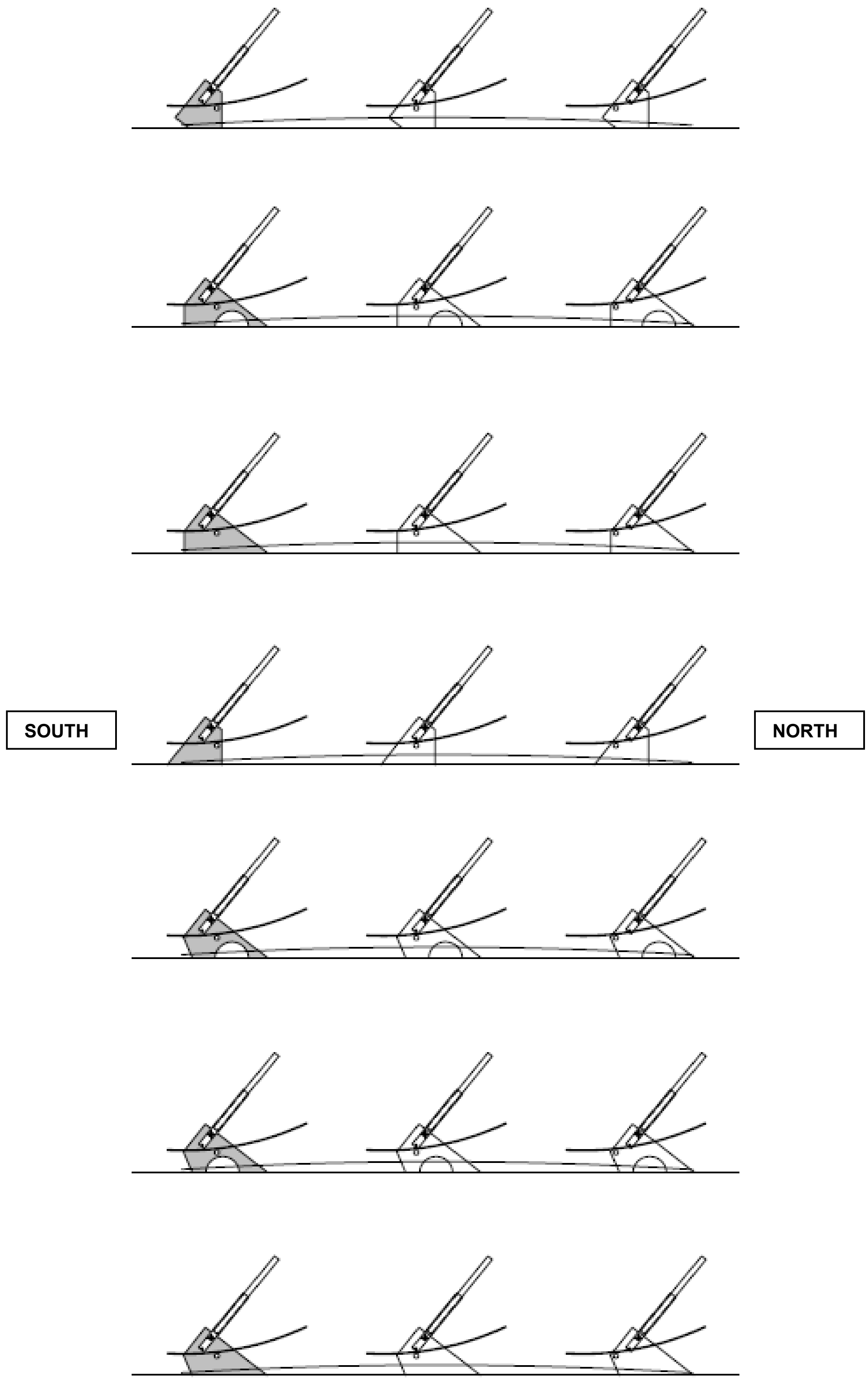

Figure 3.1 Support Profiles – Methodology I (Summer, 2007)

1. Keep the location of the pivot point for the PV panels fixed for the south, middle and north rows, while moving the shaft locations for the three rows. Figure 3.1 shows a series of forms that were explored for the profile using this method.

This implied that the supports were required to be customized to three different types depending of the location on the roof, that is, south, middle and north rows.

2. Keep the shaft location on the supports at the same location and vary the location of the pivot point for the PV panels. Figure 3.2 shows some forms investigated using this methodology.

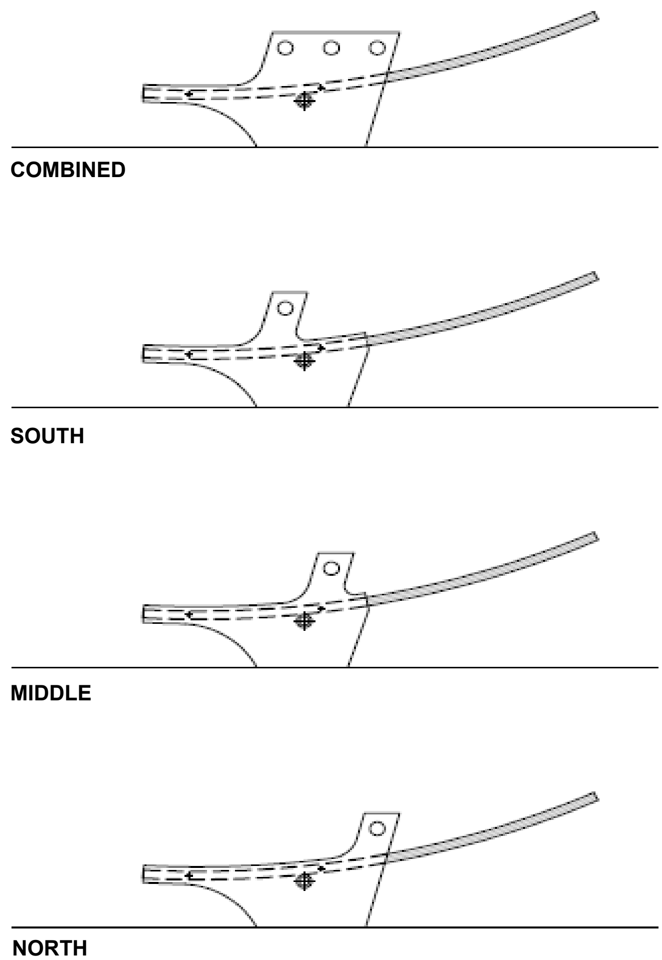

Figure 3.2 Support Profiles – Methodology II (Summer, 2007)

The issue of having customized supports plates for each row, in Methodology I and II, could be solved by having all the three distinct holes pre-drilled. This allows the plates to be manufactured using only one set of information, but at the time of installation, care needs to be taken to put components at the right location.

3. On further research it was found that if the location of connection points for the Al curved rods and the shades on the south row are altered, then a dimension could be found that can be used for spacing of both the PV panels and the shades; thus allowing for a universal design for the support plates. Figure 3.3 shows the support profile that was arrived at using Methodology III, which was common to all the three rows. This support plate was finally selected for the full scale prototype.

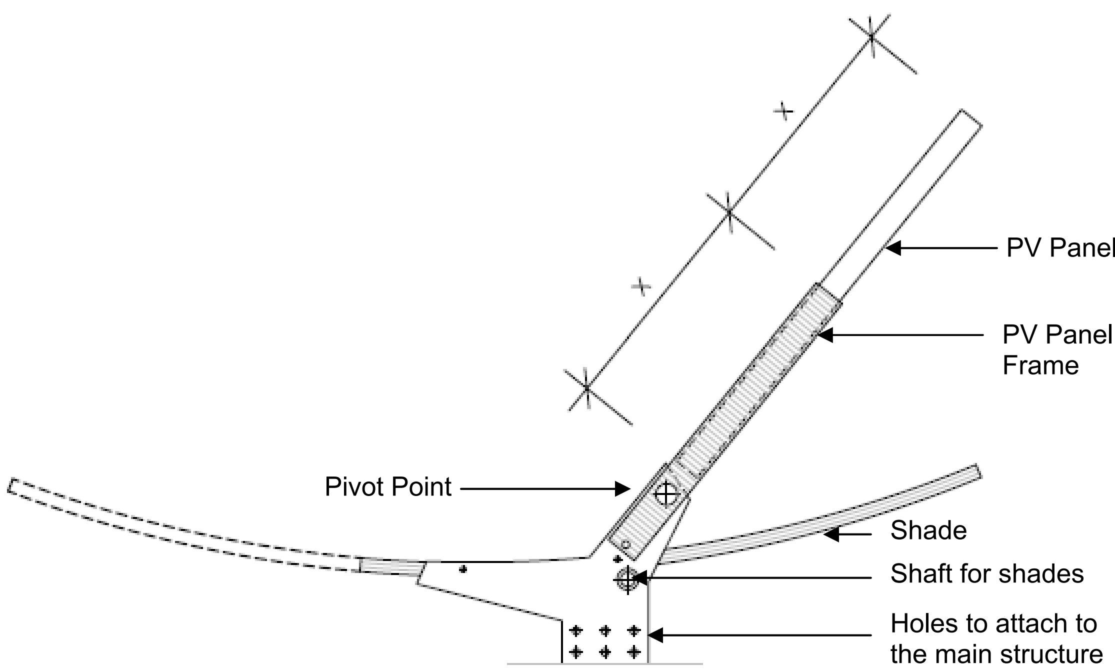

Figure 3.3 Support Profile – Methodology III (Summer, 2007)

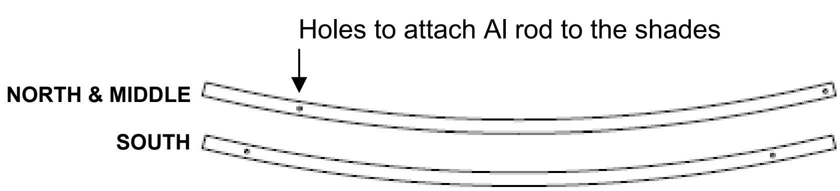

Figure 3.4: Shade side-frame (Summer, 2007)

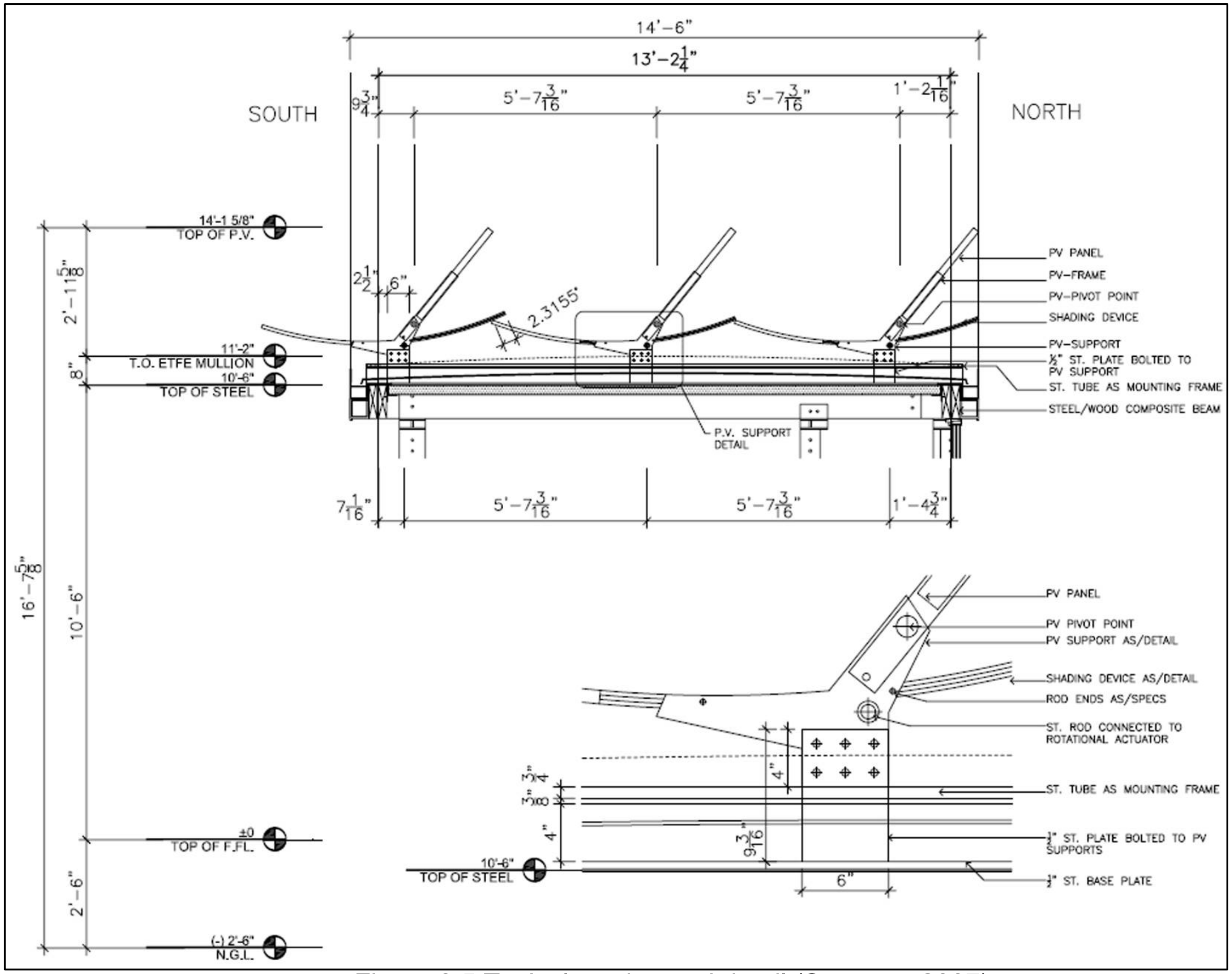

Figure 3.5 Typical section and detail (Summer, 2007)

3.1.2 Phase II – Full Scale Prototyping

3.1.2.1 Prototype in Plywood

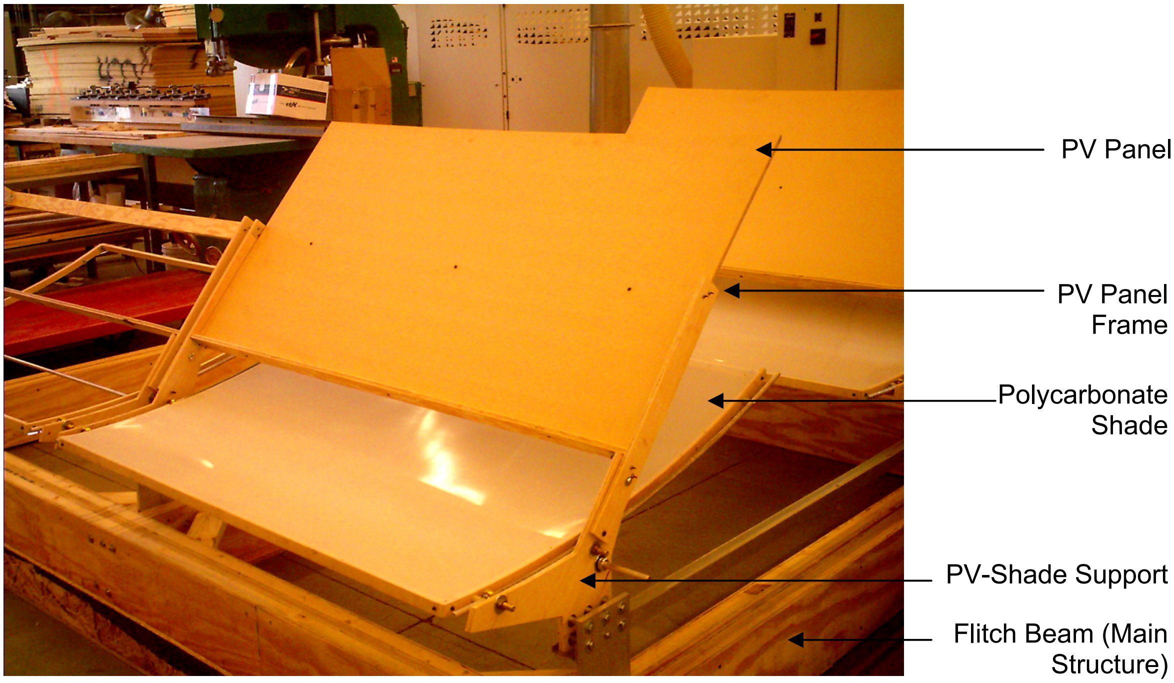

Figure 3.6 Plywood Prototype (Summer, 2007)

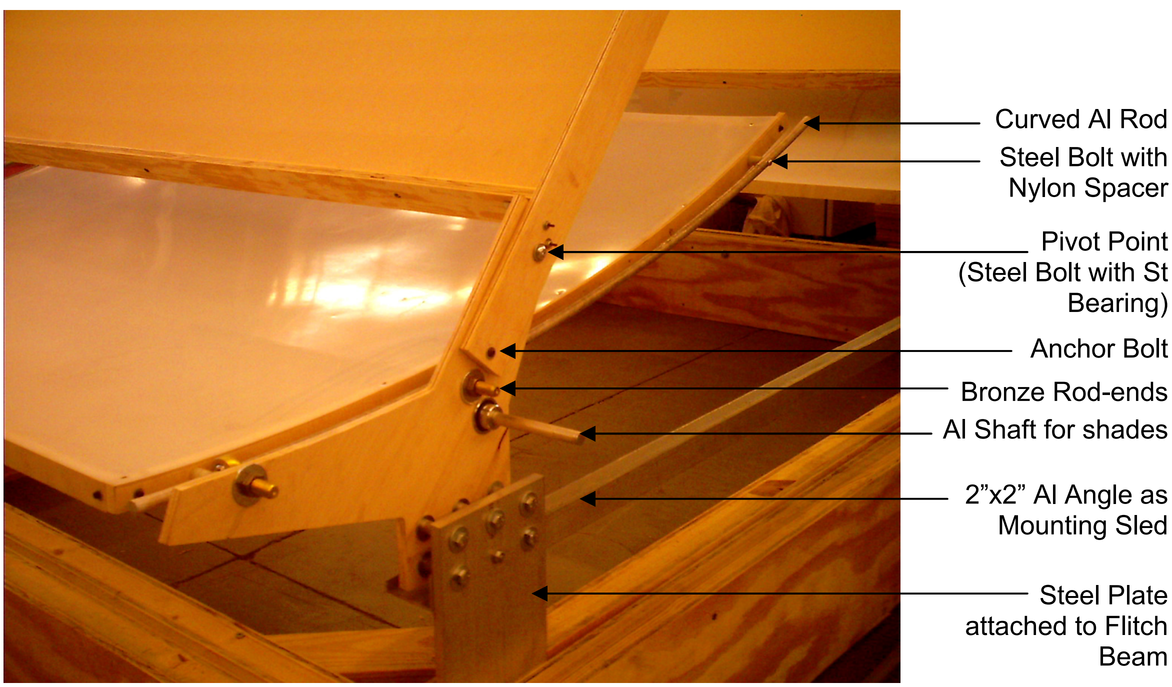

Figure 3.7 Plywood Prototype - Detail (Summer, 2007)

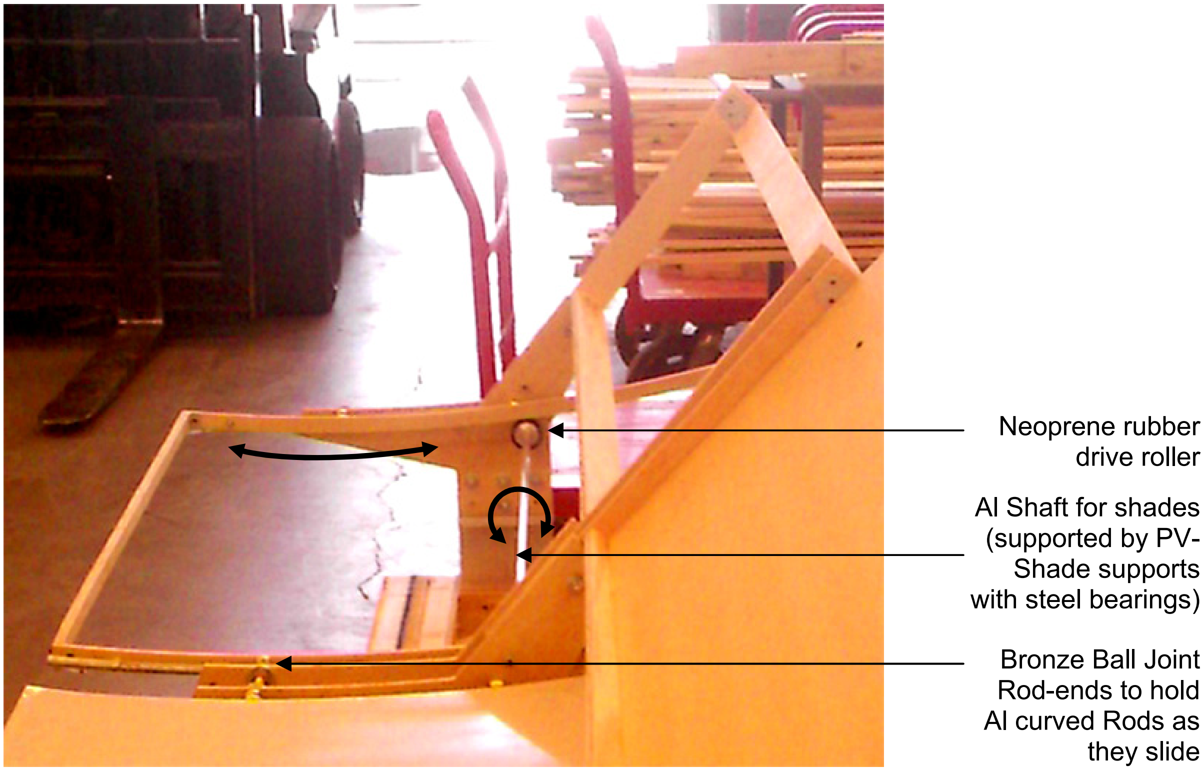

Figure 3.8 Plywood Prototype – Mechanical Detail (Summer, 2007)

Besides the absence from of PV Motion detail and the revised PV-Shades support, one important modification from the half-scale mock-up was the replacement of the Rack and Pinion with Neoprene rubber drive roller. As it was mentioned in the previous chapter, it was difficult to either locate a market source or fabricate it in-house, a rack-pinion that is curved along the specified curve.

The neoprene rubber roller as used in the full-scale mock-up is in direct contact with the curved side-frame of the shading device. As the shaft is rotated with an actuator, the rollers move the shades forward or backwards depending on the rotational direction. It primarily relied on the friction between the rollers and the bottom surface of the shade frame.

As the Aluminum rods were hand-bent, there were certain discrepancies in the curvature, which made the shade frame to loose sufficient bearing with the rollers. If the detail had to be transferred to the actual fabrication, it was felt that the Al rods need to be machine or CNC bent to maintain the required accuracy.

3.1.2.2 Prototype in Aluminum

As the next step, a prototype was needed which would be made in the material that would be used for the actual fabrication. The objective for the final prototype was:

- To establish a fail-proof method of moving the shading devices, since the previous option relied entirely on the friction between the rollers and shade frame, and this could change while using aluminum.
- Improve upon the profile of the PV frame.
- Incorporate a way to change the angle of the PV panels
- Generate a conclusive part list that would be needed to order based on the prototype.

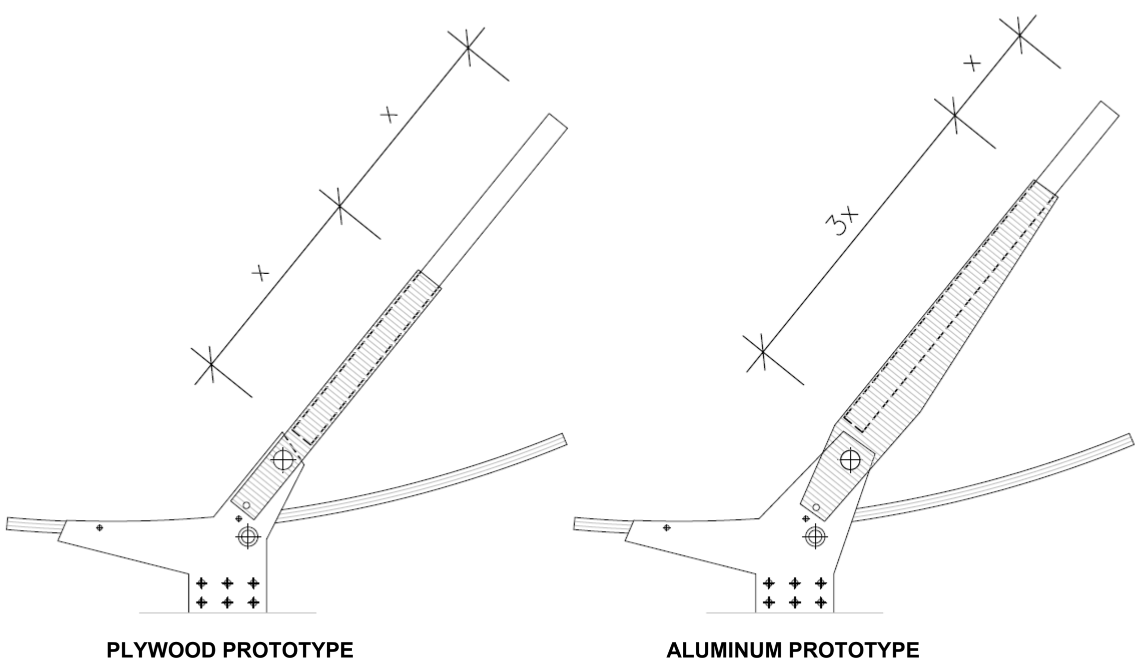

Figure 3.9 Aluminum Prototype – Modified PV Frame (Summer, 2007)

For the modification to the PV frame, the design of Modification I was revisited and the profile from that design was appropriated to work with new detail. Figure 3.9 shows the modification that was made to the frame.

To propose a detail that would allow the angle of the PV panels to be adapted as required, it was needed to arrive at an optimum angle that would be required during the course of the competition. For this purpose, a series of simulations were performed for Washington D. C. using different angles for the photovoltaic panels and the resulting solar incident radiation was calculated. As a result of these simulations, it was found that an angle of 51 deg was optimum for competition period. Refer Appendix A for the complete result of simulations.

It was found that angles at 10 deg intervals, above and below 51 deg, could provide sufficient adaptability for the PV panels. Also an interval of 10 deg meant that the holes for the anchor bolt were not too close to compromise the structural strength of the PV-Shade supports.

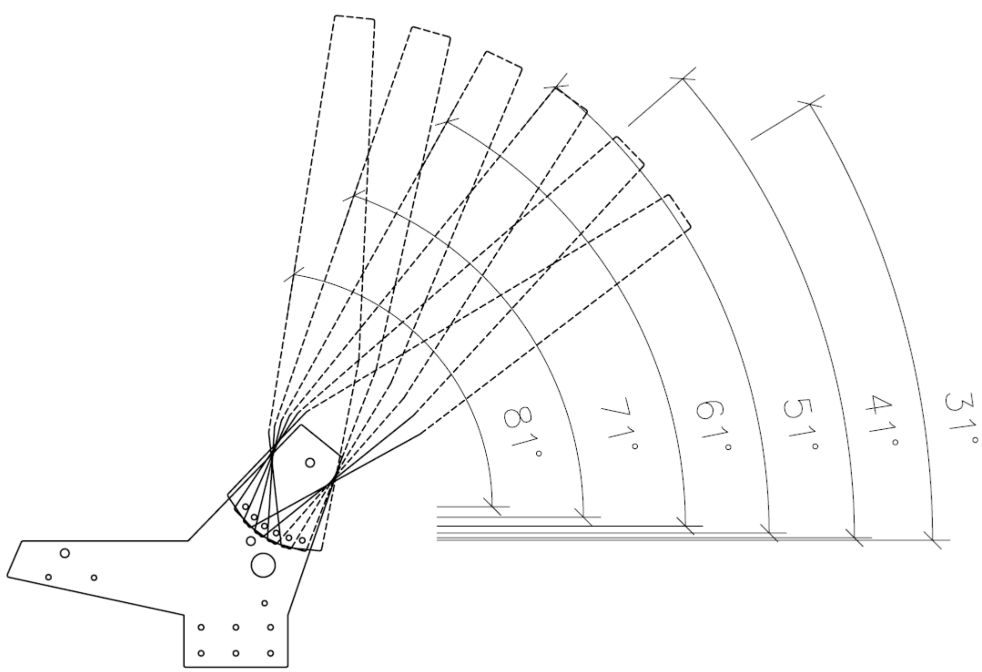

Figure 3.10 Aluminum Prototype – Possible Angles variations (Summer, 2007)

To move the shades it was decided to replace the Neoprene rubber drive rollers with drive gears and idlers, which were connected with chains. Once again this is an idea that was explored earlier (Modification II), but unlike the previous design care was taken not to expose the mechanical components. All the components responsible for moving the shades were still remained under the shades.

The process started with replacing parts from the plywood prototype with the modified aluminum parts. Even though the neoprene rubber rollers worked with the aluminum parts, it was decided to that it would be a more robust solution to have the drive gears and idlers for the final installation.

Except for the Neoprene rubber rollers, all the other hardware and parts from the plywood prototype remained the same.

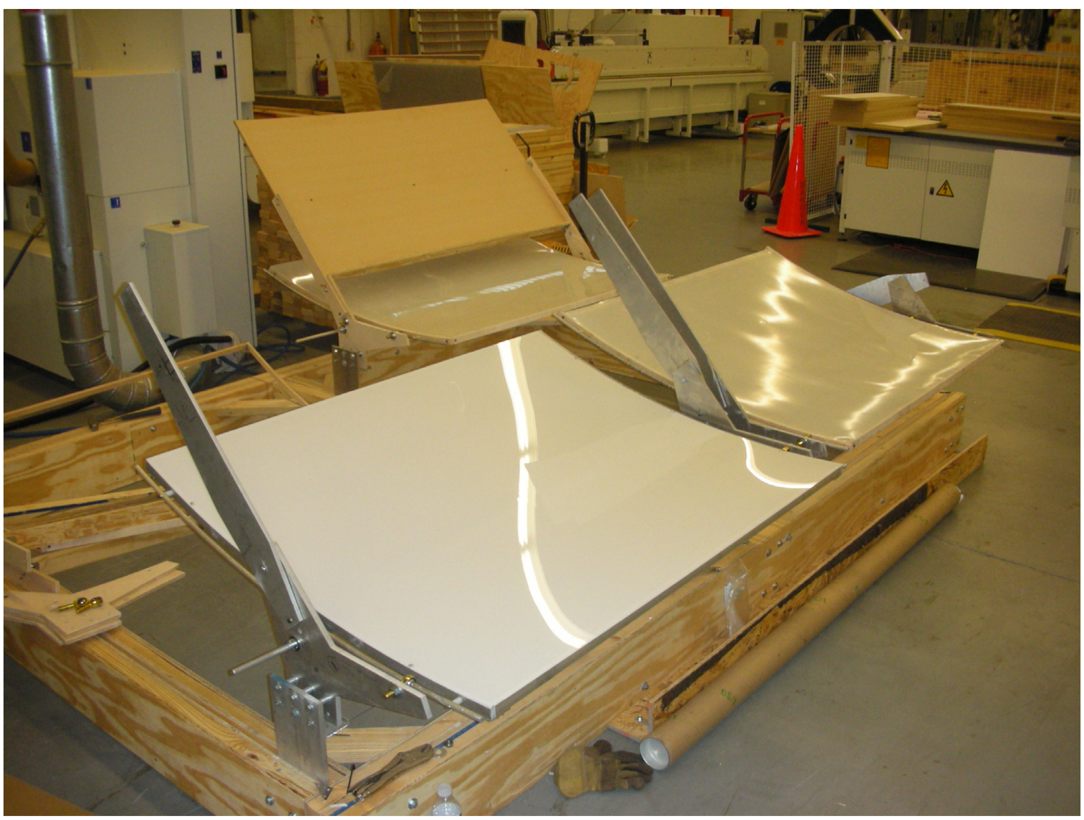

Figure 3.11 Aluminum Prototype – Replacing plywood parts (Fall, 2007)

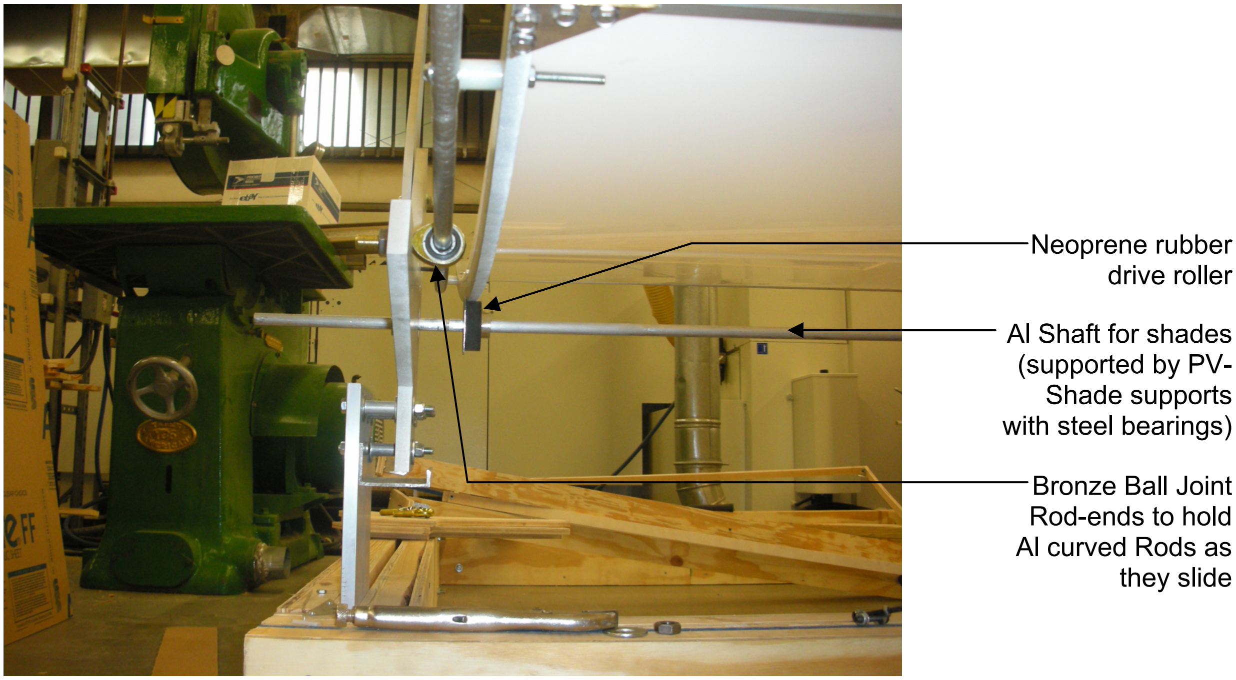

Figure 3.12 Aluminum Prototype – Testing Neoprene rollers (Fall, 2007)

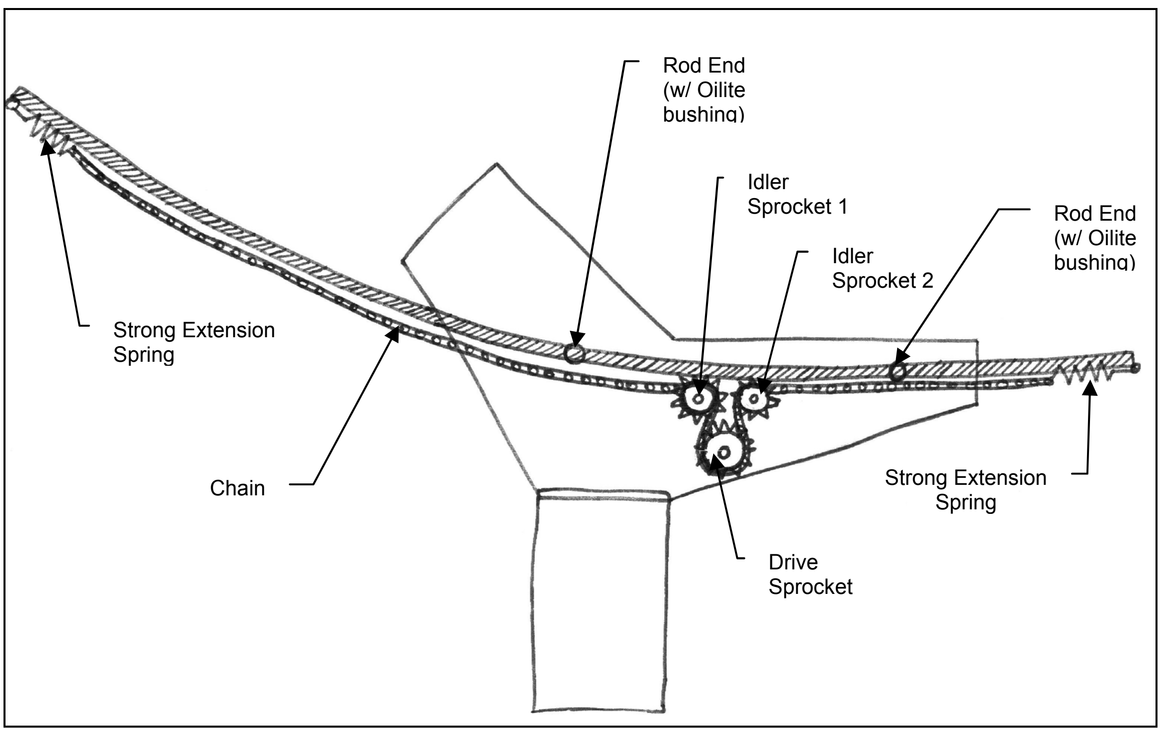

Figure 3.13 Aluminum Prototype – Proposed Modifications (Fall, 2007)

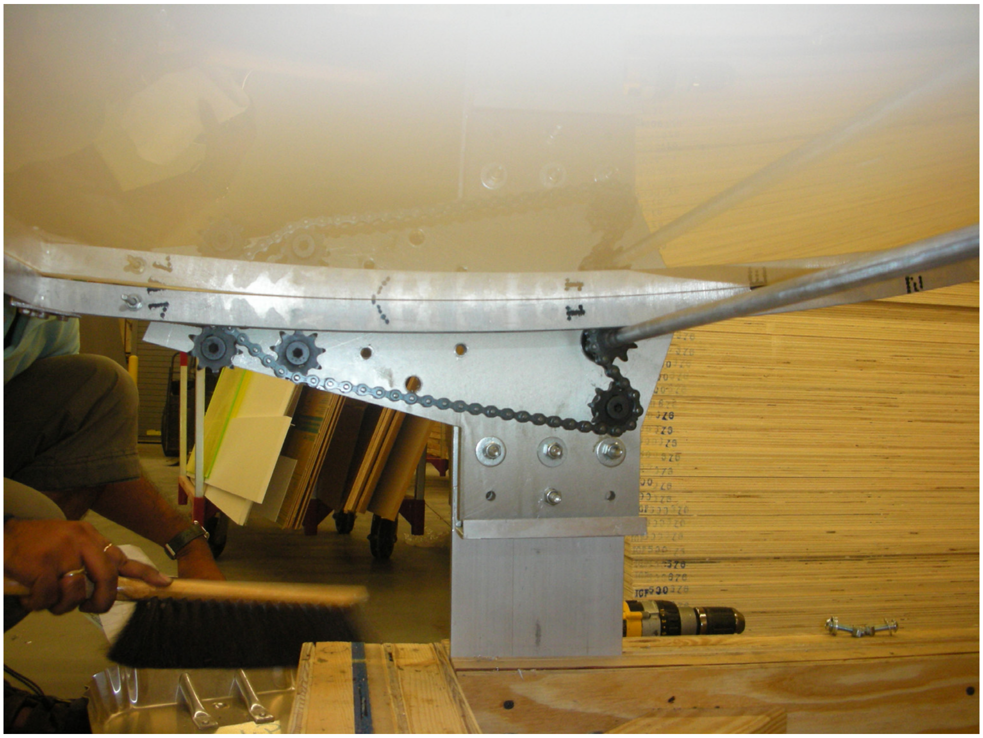

Figure 3.14 Aluminum Prototype – Idler Location – Option I (Fall, 2007)

Figure 3.15 Aluminum Prototype – Idler Location – Option II (Fall, 2007)

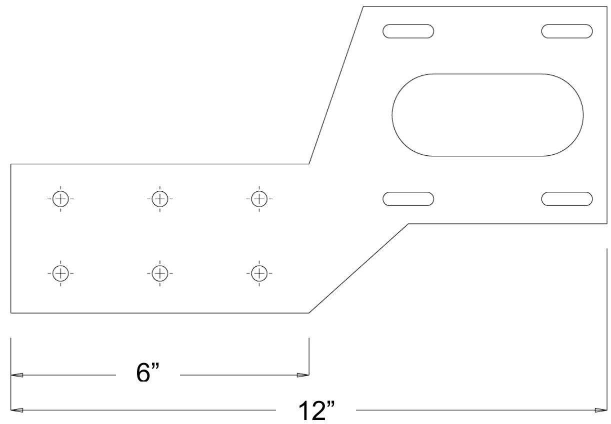

Figure 3.16 Aluminum Prototype – Motor Mount – Proposed (Fall, 2007)

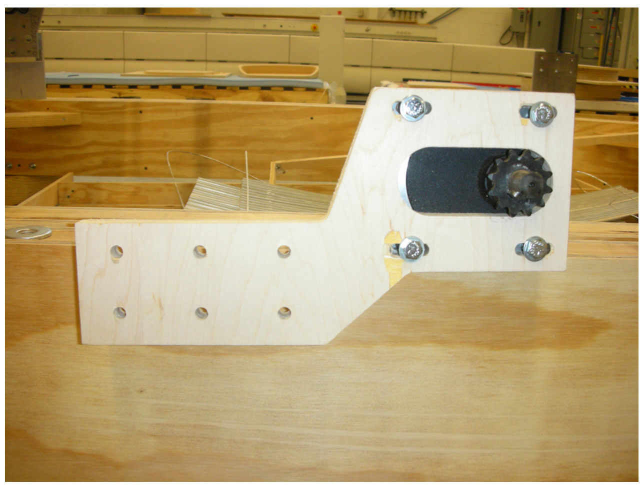

Figure 3.17 Aluminum Prototype – Motor Mount – Plywood (Fall, 2007)

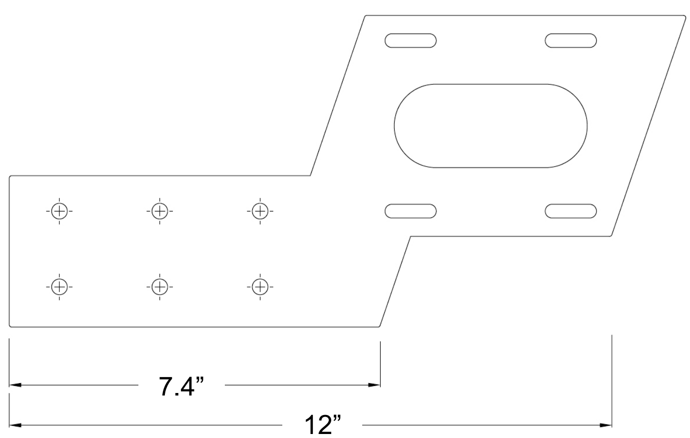

Figure 3.18 Aluminum Prototype – Motor Mount – Modified (Fall, 2007)

With this prototype, the design of all components structural and mechanical was finalized, including the chain layout option I (Figure 3.14) which was selected on the basis of better approach to the springs.

As the detail for moving the shades was fairly robust, it was decided to install one set of drive sprocket and idler set per shading unit. This implied that all the shading devices in one row need to be attached together to counter any rotational lag among the shades. For this purpose, plywood strips were used for the prototype, but aluminum was selected for the final installation. (Figure 3.19)

Based on the prototype, the final drawings were prepared that could be sent to for water-jet cutting of the aluminum.

Figure 3.19 Final Water-jet Parts – Shade Connectors (Fall, 2007)

3.1.3 Phase III – Fabrication of Final Parts

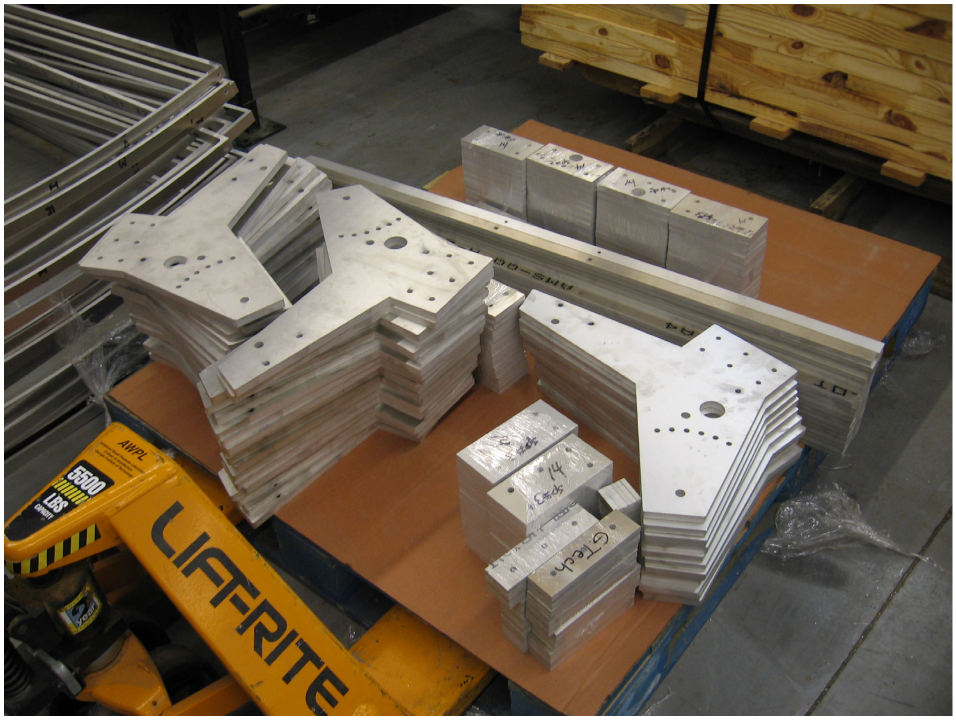

Figure 3.20 Final Water-jet Parts (Fall, 2007)

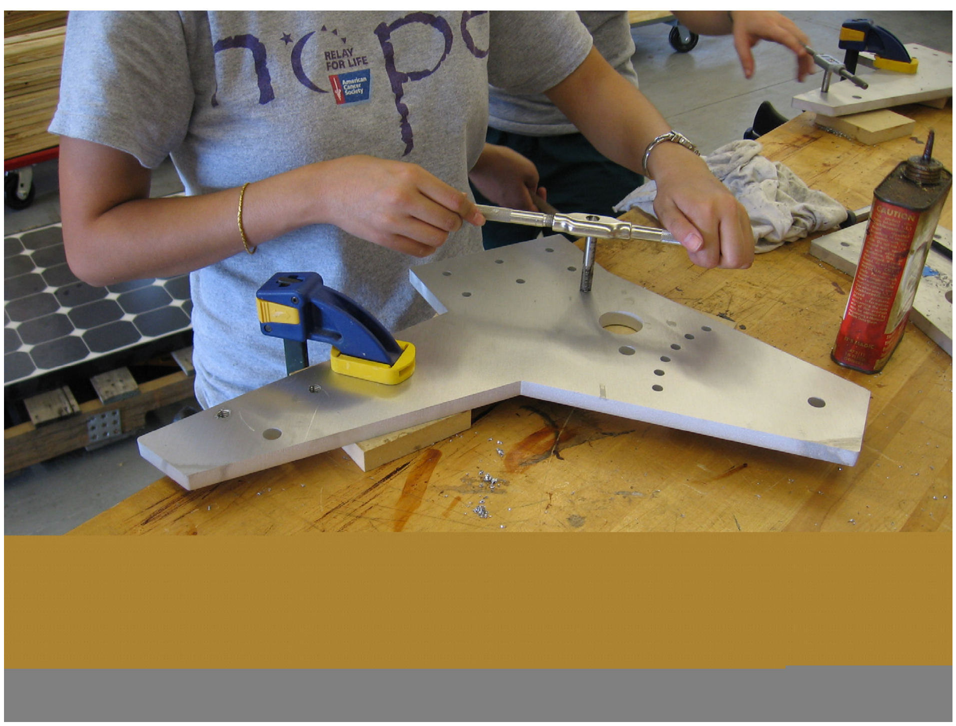

Figure 3.21 Final Parts – Tapping of holes to install idlers (Fall, 2007)

Figure 3.22 Jig – To Weld Shade Frame (Fall, 2007)

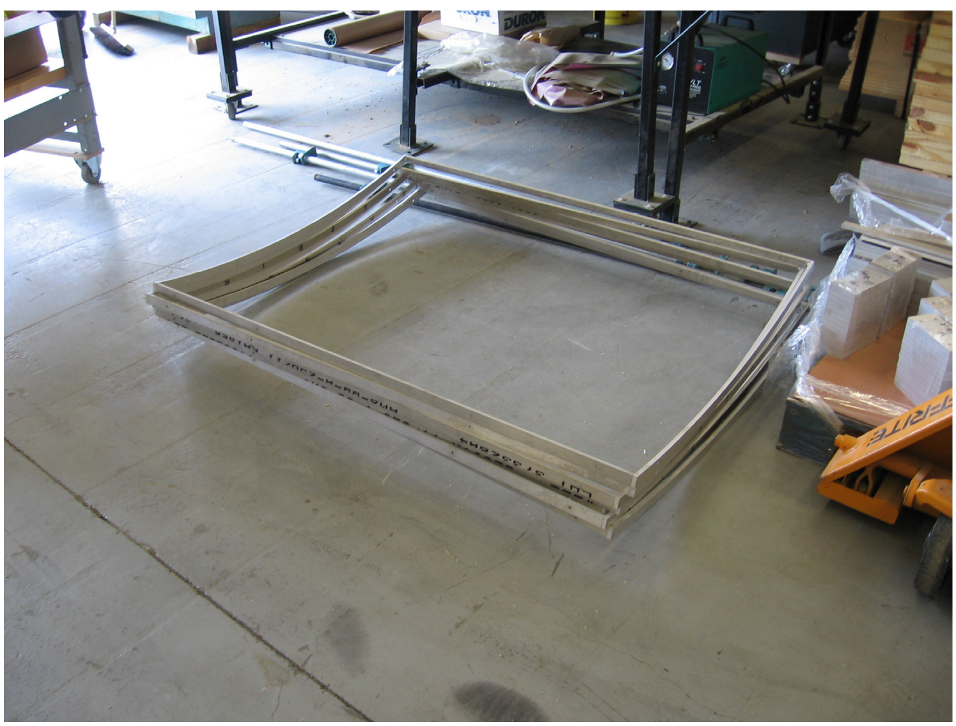

Figure 3.23 Final Parts – Welded Shade Frame (Fall, 2007)

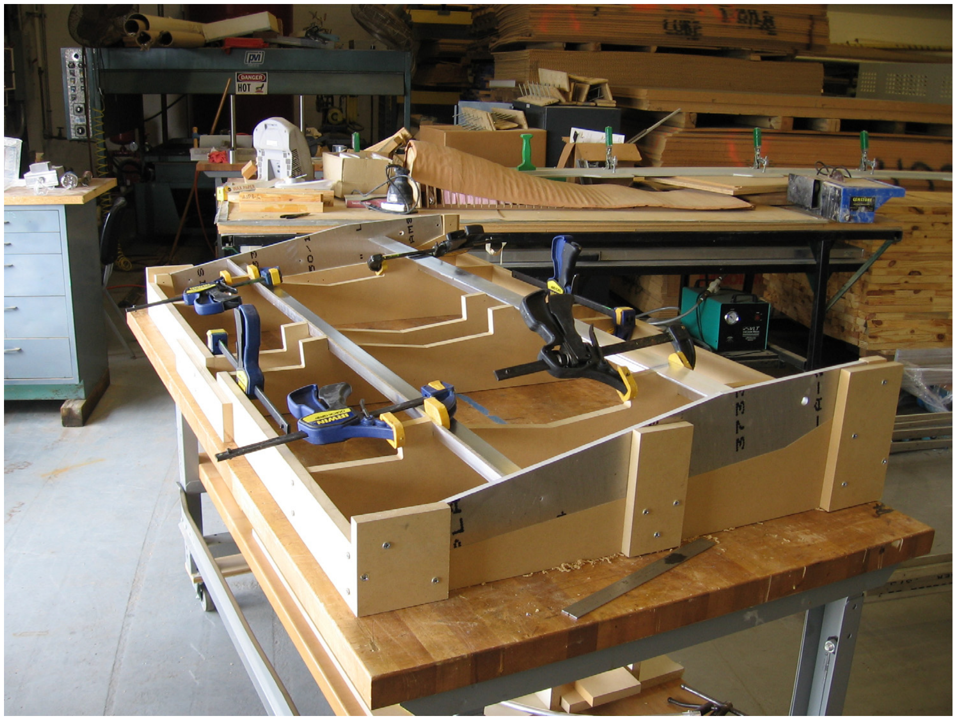

Figure 3.24 Jig – To Weld PV Frame (Fall, 2007)

Figure 3.25 Final Parts – Welded PV Frame (Fall, 2007)

Figure 3.26 Final Parts – Drilling of PV Frame (Fall, 2007)

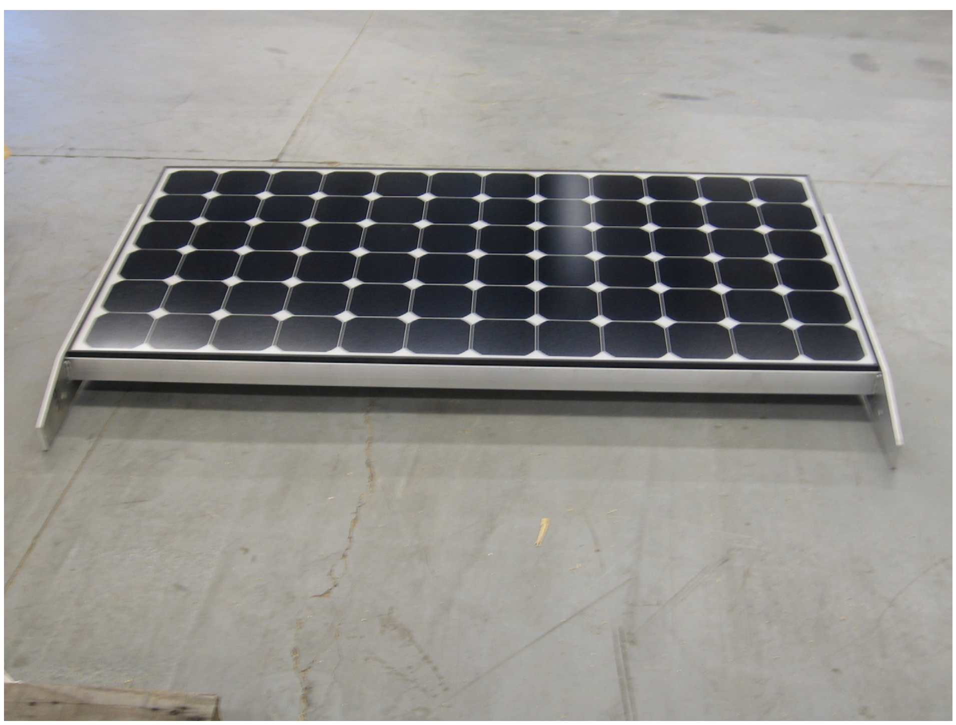

Figure 3.27 Final Parts – Installation of PV Panel (Fall, 2007)

3.1.4 Phase IV– Fabrication of Crates for Transportation

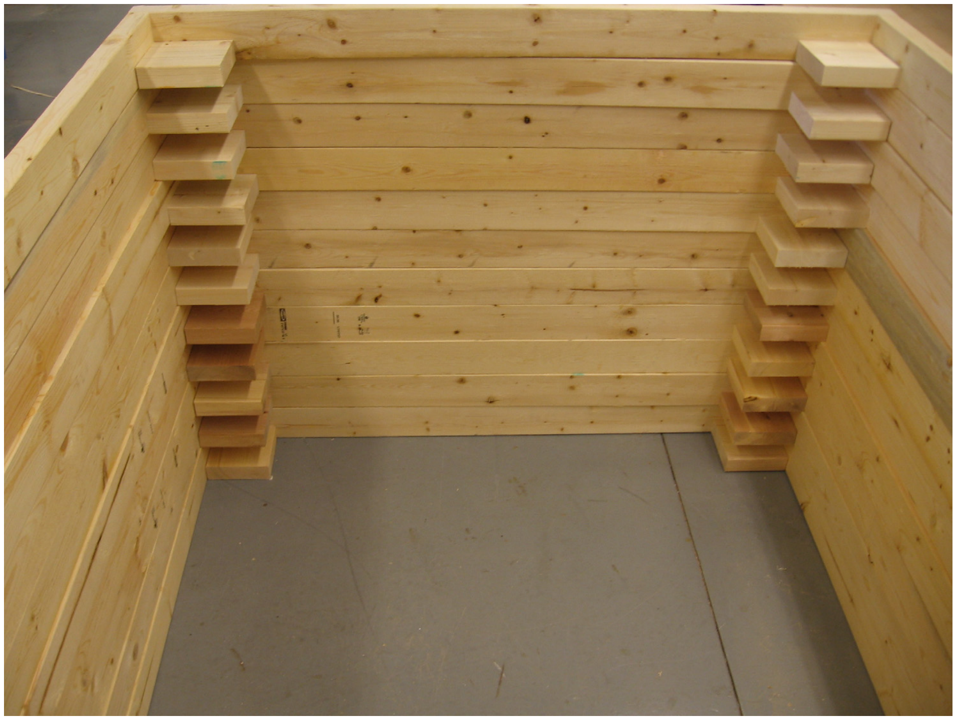

Figure 3.28 Crates – Horizontal Frame (Fall, 2007)

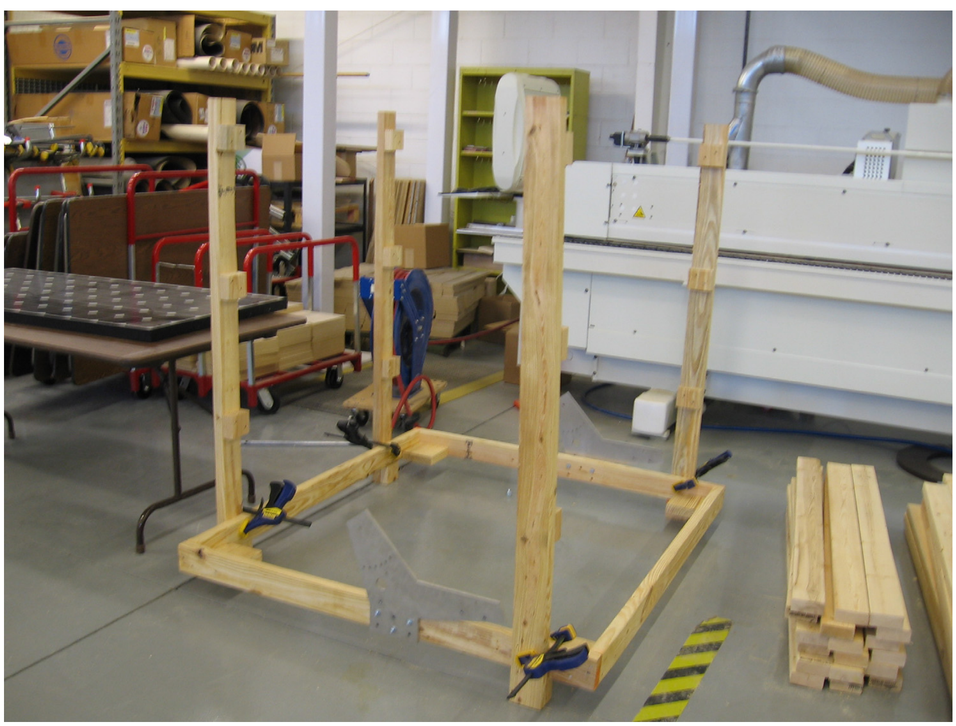

Figure 3.29 Crates – Vertical Attachments (Fall, 2007)

Figure 3.30 Crates – One set (Fall, 2007)

Along with the process to finalize the design and initiate fabrication of adaptable PV and shade systems, a parallel process to delineate the logic that could control the motion of these operable systems was started at the beginning of Spring 2007.

Although the concept of automation of the PV panels was never implemented, the controls group did lay down the basic schema upon which the control logic to move the PV panels can be built. As far as the shading devices are concerned, it was demonstrated that the shades can be remotely controlled to extend and retract; implying that a more sophisticated logic based on sensor inputs and real-time simulations can easily be deployed.

The next chapter elaborates the basic ground work that was done to identify the controls logic for both PV panel and shading device systems.

CHAPTER 4

CONTROLS FOR ADAPTIVE MOTION

4.1 Photovoltaic Motion Control

4.1.1 Definition of objectives

To optimize energy production, by controlling the movement of PV panels to track the changing position of sun. This variation in angle of PV panels would be based on an output variable, which can be from:

1. An automated Source like the Sun Tracking Sensor
2. A user Defined Control Logic – Schedules
3. A predictive Simulation based on local weather report using a real-time sensory inputs and a user defined schedule.

Based on the fact that the sun tracking devices are associated with high initial set-up cost and usually are suited to large photovoltaic installations, and also the accuracy of user defined schedules could be affected by changing weather conditions on the site, it was decided to combine a simulation based controller with a user defined schedule, while collecting real-time sensory information.

4.1.2 Protocols of movement

Two modes of movement were identified for simulation-based motion controller for the photovoltaic panels, which were:

<u>Mode-1:</u>

Move the PV panels to follow the pre-determined altitude angle of the sun on an hour to hour basis.

<u>Mode-2:</u>

Keep the PV panels at a pre-determined optimum angle for the day.

4.1.3 Modes of operation

As mentioned before, decision regarding the optimum angle is made based on a simulation that computes an optimization algorithm. This is done using the solar incident radiation predicted by the next day's weather report. Based on simulation results, the PV panels are fixed either to the angle for the start of the day or to the daily optimum angle.

A feedback loop is then established, using a pyronometer and the updated weather report, which is used to update the chosen mode of operation. The solar irradiance readings from the pyronometer are *assumed* to be true for the next hour and the updated local weather report is used to *predict* the solar radiation for the rest of the day.

The objective for the optimization algorithm was defined as:

To maximize Σ (hourly energy production – hourly energy consumption)

The above Hourly Net Energy production is calculated by the following equation:

$$\{I_{DH} \times (\cos\beta \cdot \cos\gamma \cdot \sin\Sigma + \sin\beta \cdot \cos\Sigma) + I_{dH} \times (1+\cos\Sigma)\} \times 34m^2 \times 1hr \times 0.2(\text{efficiency})$$

$$- \{(\text{power}) \times (\text{moving time from the previous step})\}$$

Where,

I_{DH} : Direct solar flux striking the horizontal

I_{dH} : Diffuse radiation striking the horizontal

β : Altitude

γ : Surface solar azimuth

Σ : Surface tilt angle between the surface normal and vertical

The following figure gives an example of a Daily Angle Chart that can be prepared for the next day. The hourly optimal angle and the daily optimal angles for the day is generated using the schedule following the sun-path. While the solar radiation intensity for the day can be generated from the local weather information for the next day.

Based on the weather prediction, the simulation can compute which of the two modes can be adopted for the day. But this information needs to be updated every hour, which is accomplished using a pyronometer. Readings from the pyronometer can provide the actual solar radiation intensity in real-time, which for practical purposes can be assumed to be true for the next one hour. This information can be fed back into the simulation to update the solar radiation reading for the rest of the day, and it can be checked whether the starting situation has or has remained constant.

Table 4.1: An example of daily Angle Chart

	Altitude	Surface solar azimuth	Hourly optimal angle	Daily optimal angle	Solar radiation intensity	Surface tilt angle	Energy Production	Energy Consumption
700	7.1	-73.3	67	51	18			
800	17.9	-62.9	55	51	62			
900	27.7	-50.7	50	51	108			
1000	35.7	-36.0	48	51	150			
1100	41.0	-18.3	48	51	125			
1200	42.7	1.6	47	51	169			
1300	40.4	21.2	48	51	109			
1400	34.6	38.5	49	51	109			
1500	26.2	52.7	51	51	62			
1600	16.3	64.6	56	51	37			
1700	5.4	74.8	70	51	0			

Also, surface tilt angle can be an input from a sensor that every hour checks the angle of the PV panel being monitored. This allows monitoring the operations and checking for any discrepancy between the optimum angle and the actual angle. Energy production and Energy consumption columns can also be updated every hour for the same reason.

4.1.4 Control Algorithm for Photovoltaic panel system

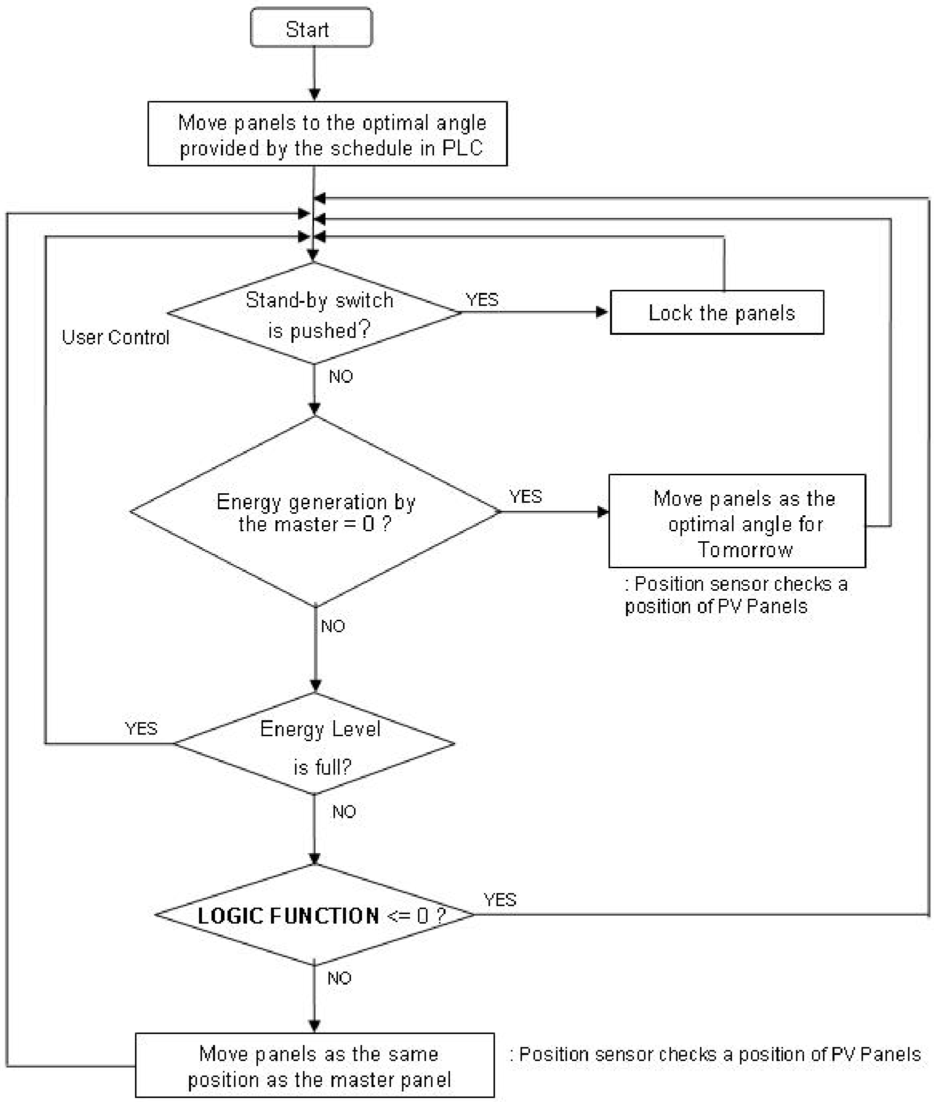

Figure 4.1 Control Flowchart – PV Panel System

The above flow chart explains the framework for developing the control logic for the PV panel system, where the Logic Function can be defined as:

(Energy generated by the master panel) – (Energy generated by a panel) – (Energy consumed for moving a panel to the same angle of the master panel)

The following is measured as inputs for the function logic;

1. Energy generated by the master panel
2. Energy generated by a panel
3. Position of the master panel
4. Position of the panels

4.2 Shading Devices Motion Control

4.2.1 Protocol of movement

Position of shading devices directly influences heating and cooling loads of the house. Hence, position of shading devices is required to be controlled proactively in real-time to properly harness solar radiation and thus reduce heating or cooling loads.

4.2.2 Modes of operation

A control variable called “OptimumShade”, is determined by a simulation running in Real-Time, using the solar incident radiation. By measuring the solar radiation intensity from the pyronometer and sending it to the simulation, the simulation spontaneously updates control variables, which then generates the output variable, in order to control the actuators that move the shades.

4.2.3 Control Algorithm for Roof-integrated Shading system

The figure below illustrates the logic for the operable shades:

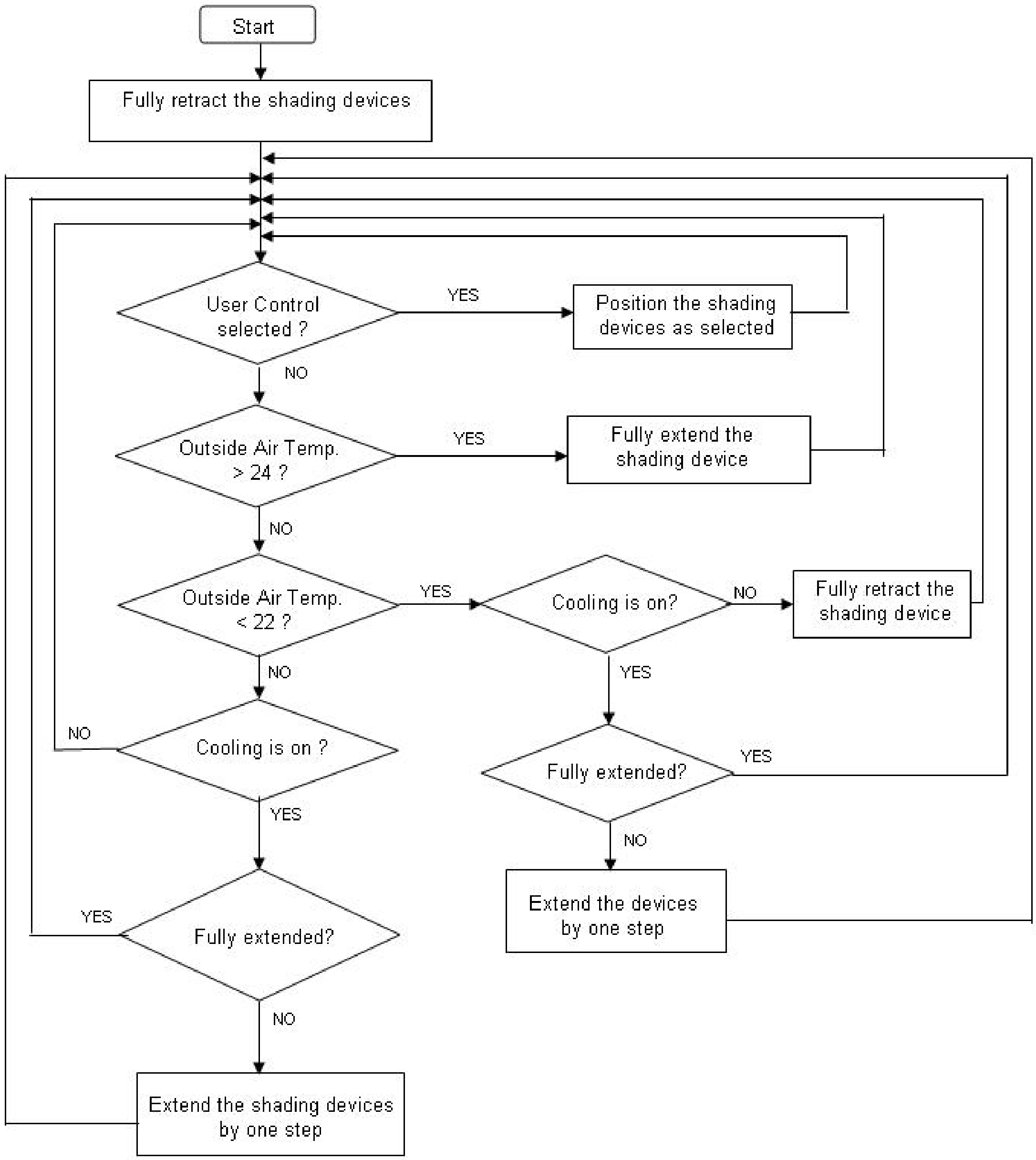

Figure 4.2 Control Flowchart – Shading System

The control logic for the shading devices has been developed based on the fact that the main purpose of the operable shades are to control the indoor air temperature, but within this constraint provision was made to ensure as much daylight inside the house as possible.

4.3 Programming the control logic

Some of the initial programming was done using LabView, which was an attempt to convert the logic as shown in Figure 4.1 and Figure 4.2 to software codes that can used receive inputs over the network, read digital and analog inputs from the sensors and if required publish a variable over the network for other systems network.

The figure below shows User Interface for PV Panel operations. There is only one user control which is the stand-by mode. If this is clicked, PV panels are locked at the current position and will not be moved until the stand-by mode is off. The panel displays the current angle of the PV panels and the optimal angle calculated as described above. This allows the user to check whether PV Panels are properly operating.

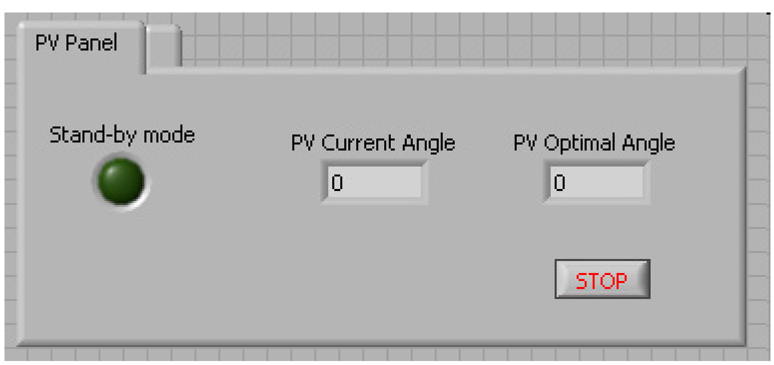

Figure 4.3 User Interface – PV Panel System

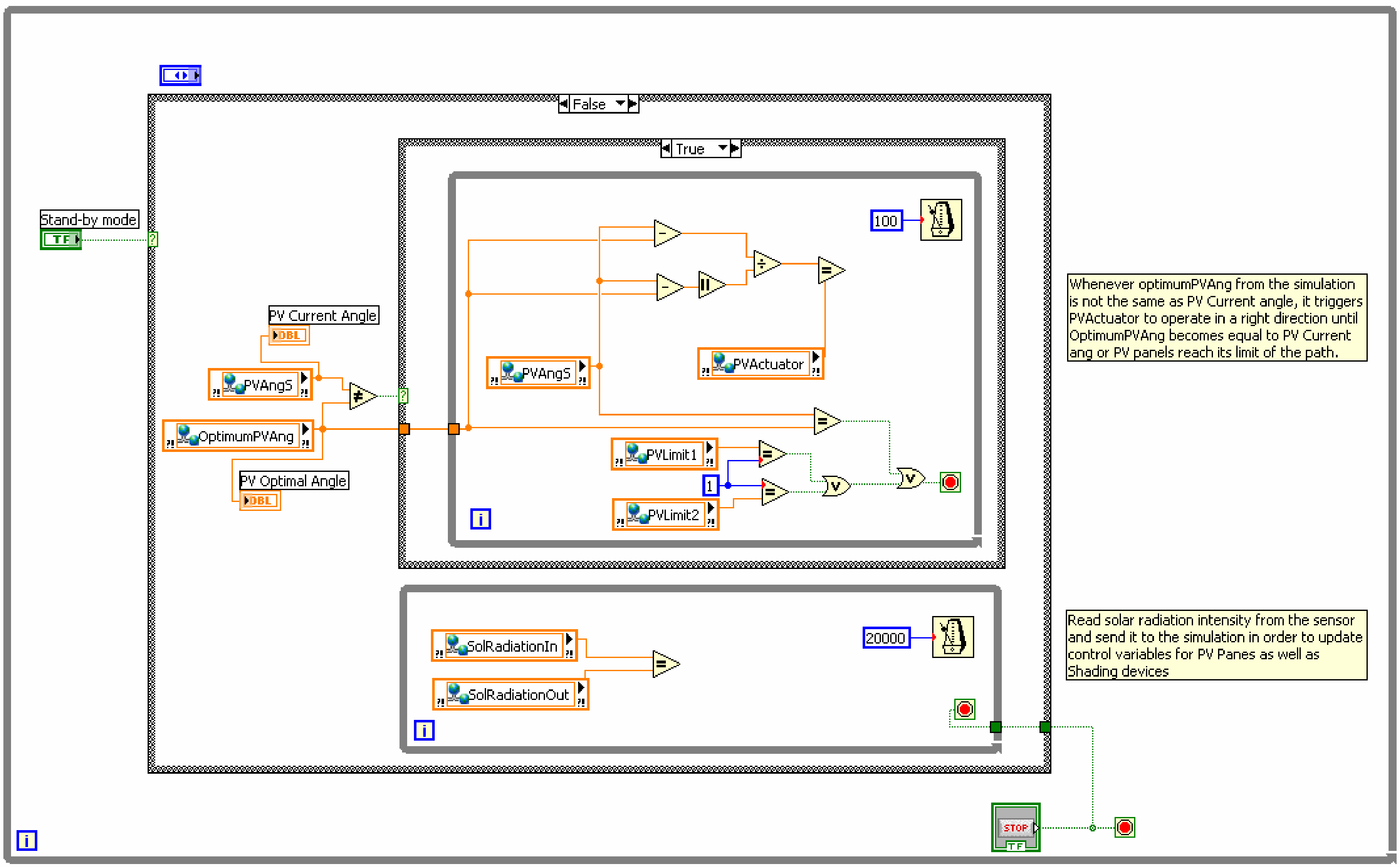

Figure 4.4 Block Diagram – PV Panel System

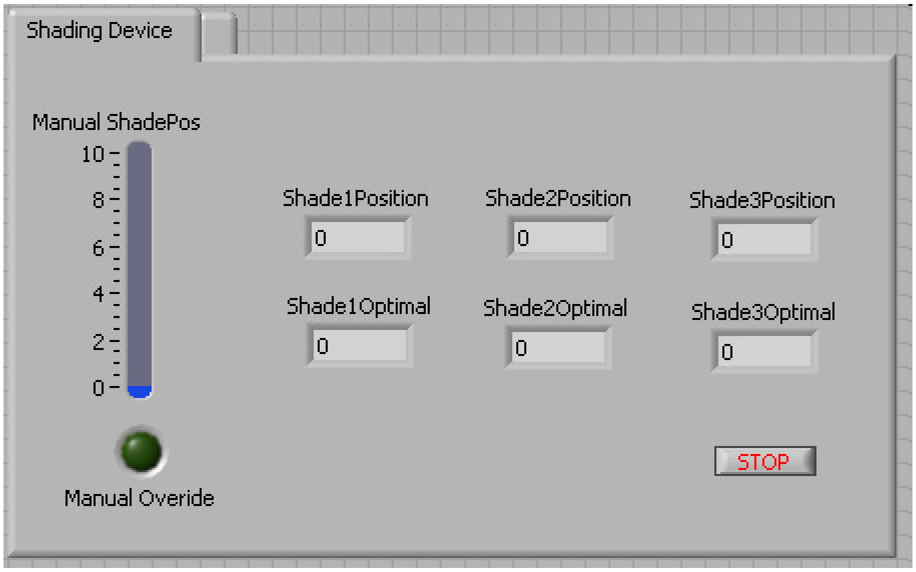

Figure 4.5 User Interface – Shading Devices

Figure 4.5 shows the user interface of for operations of the shading devices. On this panel, the user can manually change one of the certain discrete position for the shading devices. This mode is activated only if the manual override is switched on. On the other hand, when Manual Override button is switched off, the shading devices are automatically controlled by the simulation.

By matching OptimumShade position from the simulation with each row of shading devices position from the sensor, it can be checked whether shading devices are properly operating. Shade1, Shade2 and Shade3 refer to the three roes of shades, that is, south, middle and the north row.

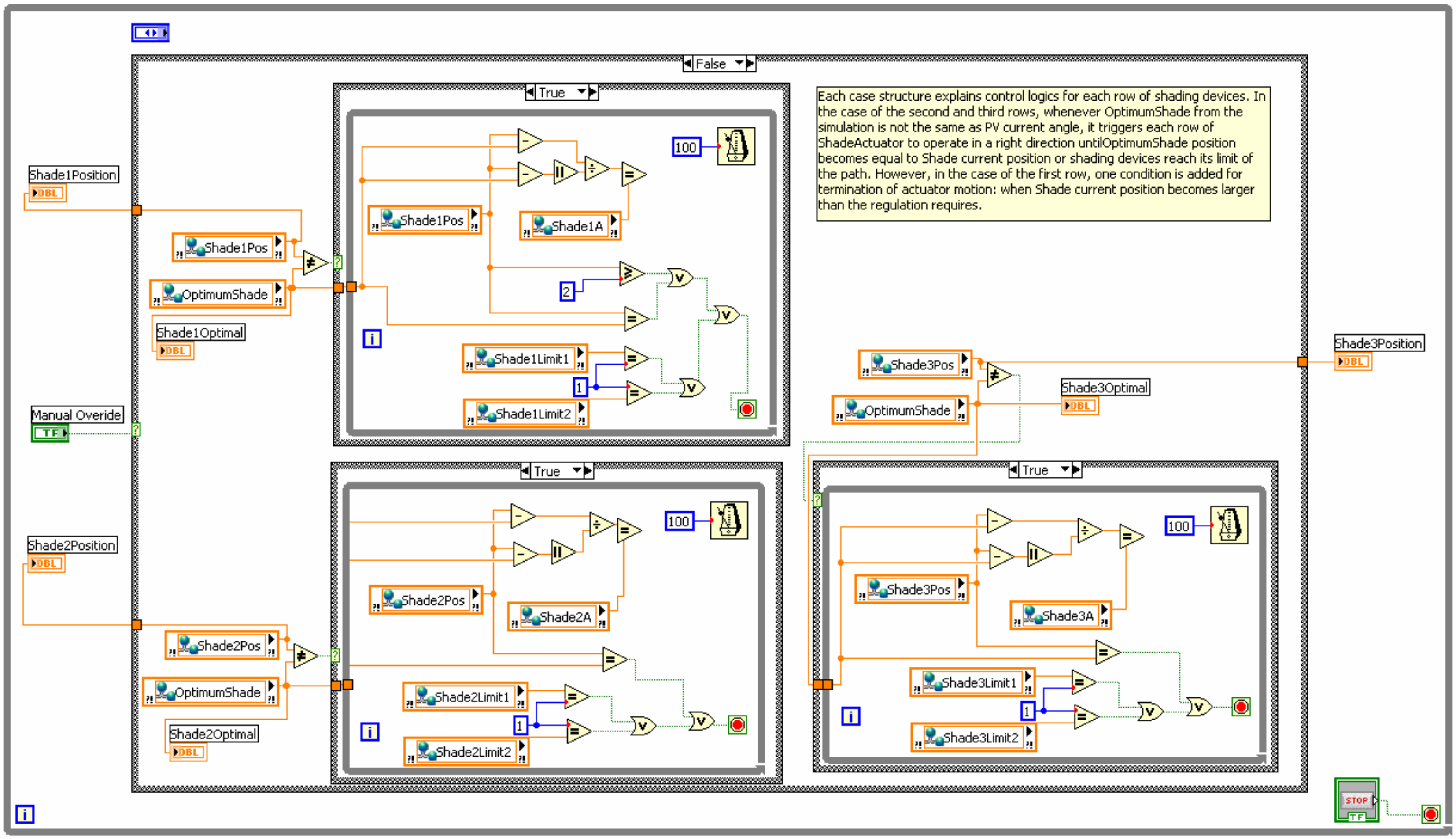

Figure 4.6 Block Diagram – Shading Devices

4.4 Controls for Solar Decathlon

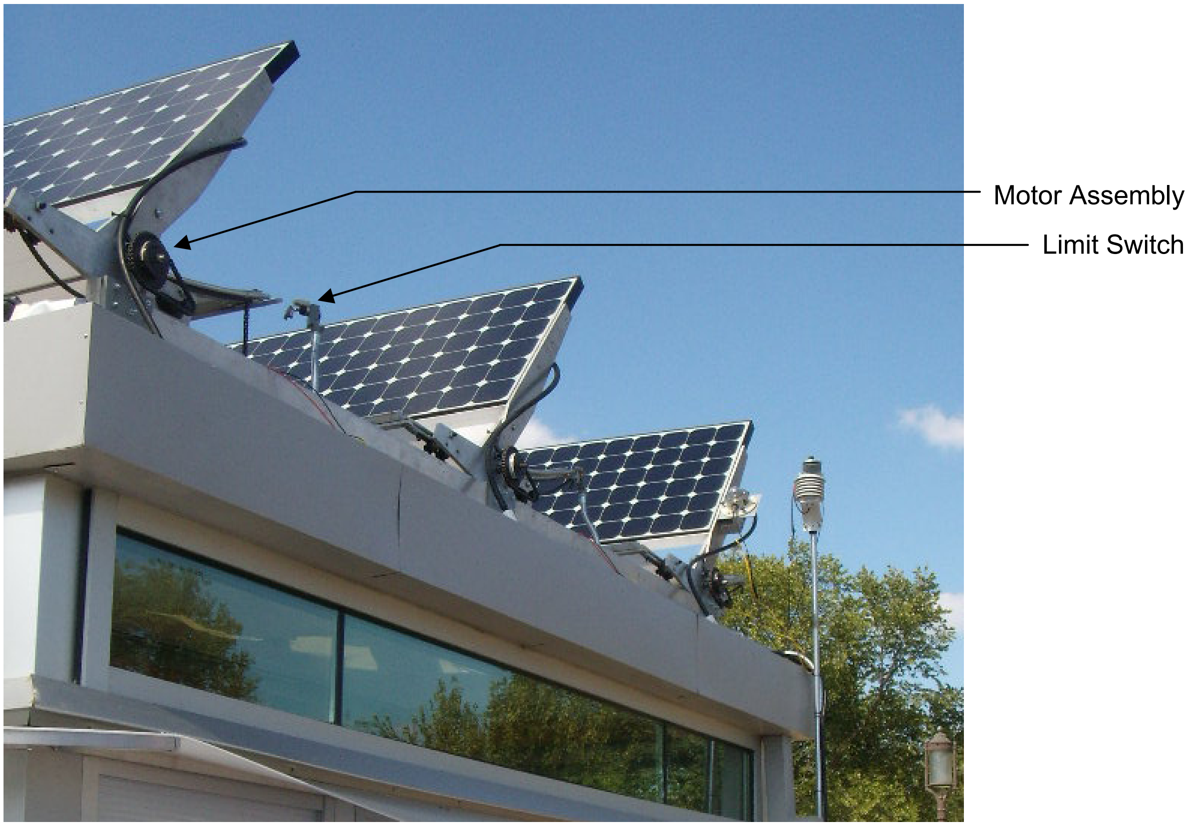

Figure 4.7 PV-Shading System as installed in D.C.

The limiting constraint of time not only affected the automation of photovoltaic panel system, which as mentioned was chosen not be implemented for the competition, but it affected the implementation of the automation scheme of shading devices as developed in the previous sections.

But it was successfully demonstrated that the shades can be controlled by a remote control system using the codes programmed in LabView. This can be considered a sufficient proof of concept that the control strategy as developed in theory can be implemented. The LabView program that was implemented was capable of moving the shades depending on a time limit. The user can adjust the time depending on how far the shades have to move till they reach their desired location. This proved to be an effective demonstration tool to show the operability of shades.

CHAPTER 5

CONCLUSION

Georgia Institute of Technology's entry for the Solar Decathlon, 2007 provided an excellent platform to base a year long research into adaptable system. These systems of photovoltaic panels that could adapted to different angles to depending the different locations and different climactic conditions, and the system of shading devices that adapted to the changing requirements of indoor environment, showed that it is possible to have a performance based approach to designing of the building envelopes.

The solutions that have been provided traditionally usually tend to very specific and codified for a particular region or a scenario. Real time adaptive systems not only make the design accessible to a larger audience, but it reduces the response time that the building industry may take to address a new programmatic setting.

This approach to building design starts to make sense if we observe the recent developments in building design and manufacturing which tend to approach a building as a product, with a specific focus on mass-customization.

However, this experience with solar decathlon does elicit one critical point, which is, even if an adaptive system provides a non-specific solution to an issue, it still has to deal with extremely hard coded requirements of the architectural design team, in all its non-specificity, it is still required to perform under the larger framework of architectural intent.

APPENDIX A

SIMULATION FOR OPTIMAL TILT ANGLE

Table A.1 Solar Incident for 1 PV Panel (Btu / Hr.Ft^2)

Date	Tilt Angle																		
	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
10/12	130.3	130.8	131.2	131.6	132.0	133.2	133.4	133.6	133.7	133.8	133.8	133.8	133.8	133.7	133.6	133.5	133.0	132.8	132.6
10/13	6.3	6.3	6.4	6.4	6.4	6.5	6.5	6.5	6.5	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.5	6.5	6.5
10/14	38.8	39.0	39.1	39.3	39.5	38.6	38.7	38.8	38.9	39.0	39.1	39.1	39.2	39.2	39.3	39.3	40.4	40.4	40.4
10/15	1417.7	1423.9	1429.6	1434.9	1439.8	1444.3	1448.1	1451.5	1454.4	1456.9	1459.0	1460.6	1461.7	1462.5	1462.7	1462.6	1463.6	1462.7	1461.3
10/16	1430.2	1436.4	1442.2	1447.6	1452.5	1456.4	1460.3	1463.8	1466.8	1469.4	1471.5	1473.2	1474.5	1475.3	1475.6	1475.5	1476.6	1475.7	1474.4
10/17	130.1	130.7	131.2	131.7	132.1	132.0	132.4	132.7	132.9	133.1	133.3	133.4	133.5	133.6	133.6	133.6	134.2	134.1	133.9
10/18	793.1	797.0	800.7	804.1	807.3	813.1	815.9	818.4	820.6	822.6	824.4	825.9	827.2	828.2	828.9	829.5	826.0	825.9	825.6
10/19	1836.1	1845.2	1853.7	1861.7	1869.1	1865.7	1872.3	1878.3	1883.7	1888.5	1892.8	1896.4	1899.5	1902.1	1904.0	1905.4	1913.1	1913.0	1912.3
10/20	1852.5	1861.9	1870.8	1879.0	1886.7	1889.5	1896.3	1902.5	1908.1	1913.1	1917.5	1921.4	1924.6	1927.3	1929.4	1930.9	1933.8	1933.9	1933.4
	7635.1	**7671.2**	**7704.9**	**7736.3**	**7765.4**	**7779.3**	**7803.9**	**7826.1**	**7845.6**	**7863.0**	**7878.0**	**7890.4**	**7900.6**	**7908.5**	**7913.7**	**7916.9**	**7927.2**	**7925.0**	**7920.4**

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